Parity Violation: Past, Present, and Future

M.J. Ramsey-Musolf

NSAC Long Range Plan

- What is the structure of the nucleon?
- What is the structure of nucleonic matter?
- What are the properties of hot nuclear matter?
- What is the nuclear microphysics of the universe?
- What is to be the new Standard Model?

NSAC Long Range Plan

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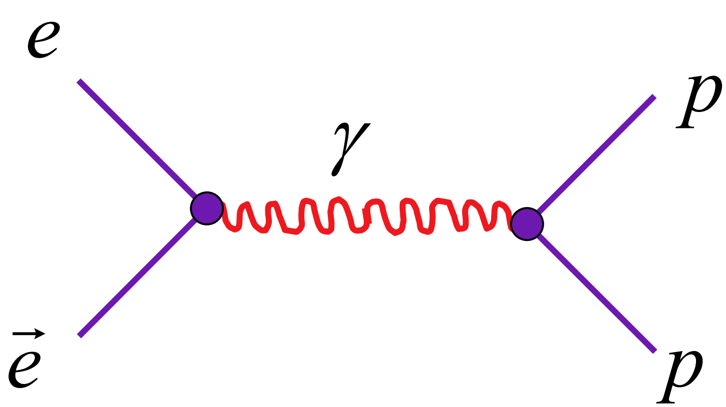
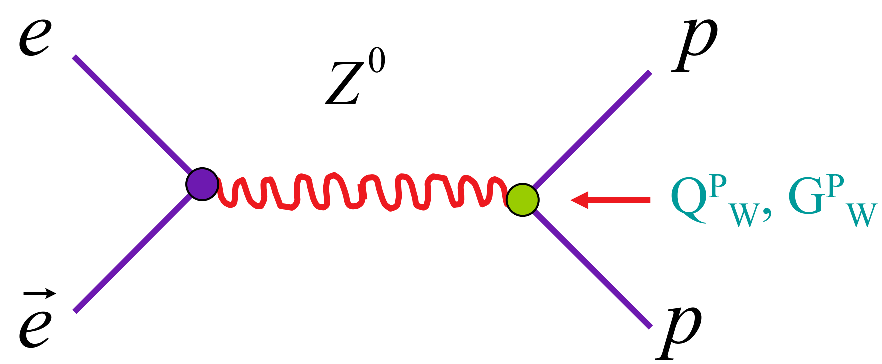
Parity-Violating Electron Scattering

Outline

- PVES and Nucleon Structure
- PVES and Nucleonic Matter
- PVES and the New Standard Model

Parity-Violating Asymmetry



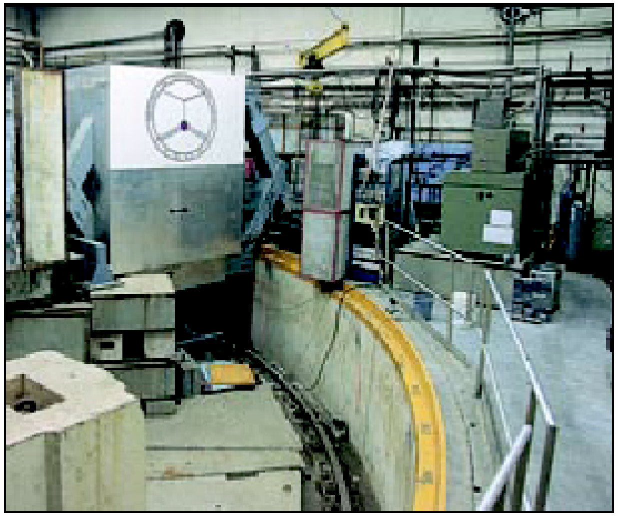


$$A_{LR} = \frac{N_+ - N_-}{N_+ + N_-} = \frac{2\,\mathrm{Re}\;A_{PV}\,A_{PC}^{\,*}}{|A_{PC}|^2}$$

G^P_W

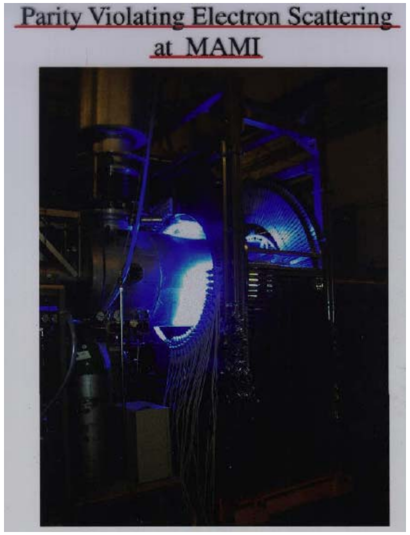
$$= \frac{G_F\left|Q^2\right|}{4\sqrt{2}\pi\alpha}\left[\,Q^P_W + F(Q^2,\theta)\,\right]$$

PV Electron Scattering Experiments



MIT-Bates

Mainz



Jefferson Lab

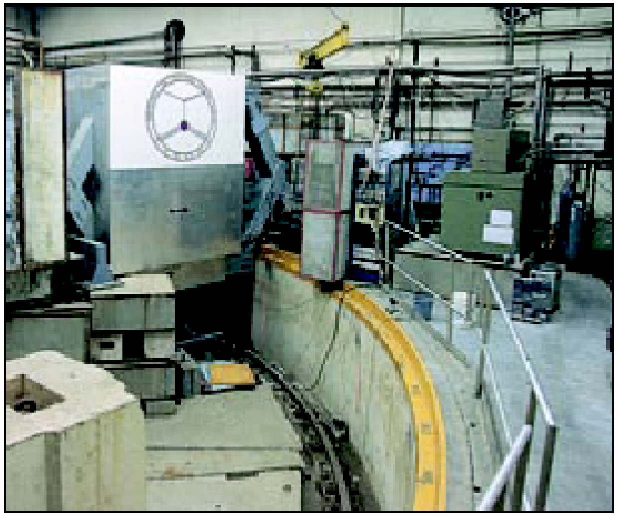
SLAC

PV Electron Scattering Experiments

Deep Inelastic eD (1970's)
PV Moller Scattering (now)
Deep Inelastic eD (2005?)

SLAC

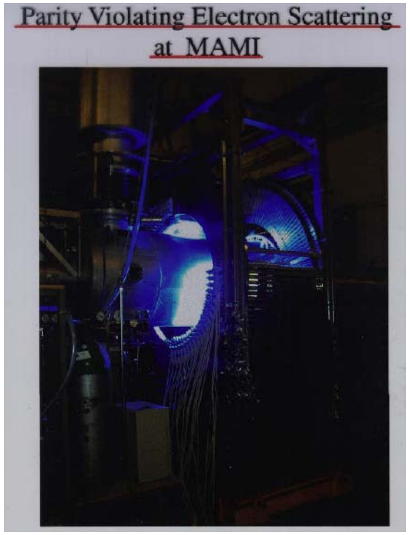
PV Electron Scattering Experiments



MIT-Bates

Elastic e ^{12}C (1970's - 1990)
Elastic ep, QE eD (1990's - now)

PV Electron Scattering Experiments



Mainz

QE e ^{9}Be (1980's)
Elastic ep (1990's - now)

PV Electron Scattering Experiments

Elastic ep: HAPPEX, G0 (1990's - now)
Elastic e ^{4}He: HAPPEX (2003)
Elastic e ^{208}Pb: PREX
QE eD, inelastic ep: G0 (2003-2005?)
Elastic ep: Q-Weak (2006-2008)
Moller, DIS eD (post-upgrade?)

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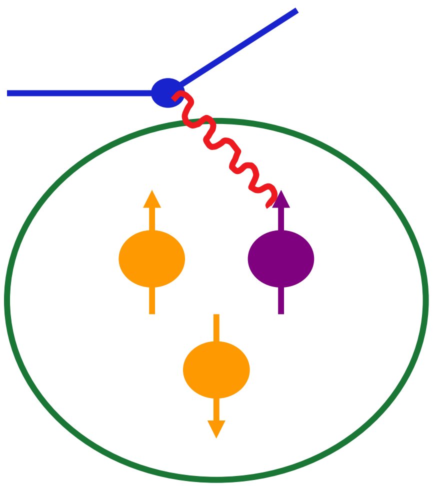
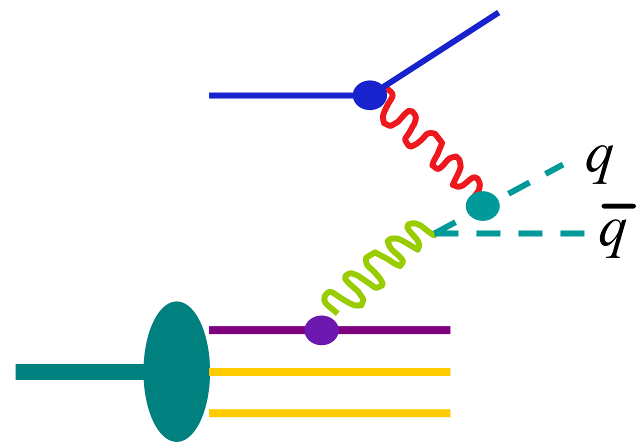
PVES and Nucleon Structure

What are the relevant degrees of freedom for describing the properties of hadrons and why?



Constituent quarks (QM)

Q^P , μ^P



Current quarks (QCD)

$F^P{}_2(x)$

PVES and Nucleon Structure

Why does the constituent Quark Model work so well?

- Sea quarks and gluons are "inert" at low energies
- Sea quark and gluon effects are hidden in parameters and effective degrees of freedom of QM (Isgur)
- Sea quark and gluon effects are hidden by a "conspiracy" of cancellations (Isgur, Jaffe, R-M)
- Sea quark and gluon effects depend on C properties of operator (Ji)

PVES and Nucleon Structure

What are the relevant degrees of freedom for describing the properties of hadrons and why?

Strange quarks in the nucleon:

- Sea quarks
- $m_s \sim \Lambda_{QCD}$
- 20% of nucleon mass, possibly -10% of spin

What role in electromagnetic structure ?

We can uncover the sea with G^P_W

Light QCD quarks:		Heavy QCD quarks:	
u	$m_u \sim 5$ MeV	c	$m_c \sim 1500$ MeV
d	$m_d \sim 10$ MeV	b	$m_b \sim 4500$ MeV
s	$m_s \sim 150$ MeV	t	$m_t \sim 175{,}000$ MeV

Effects in G^P suppressed by

$(\Lambda_{QCD}/m_q)^4 < 10^{-4}$ $\Rightarrow$ Neglect them

$\Lambda_{QCD} \sim 150$ MeV

We can uncover the sea with G^P_W

Light QCD quarks:		Heavy QCD quarks:	
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s	$m_s \sim 150$ MeV	t	$m_t \sim 175{,}000$ MeV

$m_s \sim \Lambda_{QCD}$: No suppression

not necessarily negligible

We can uncover the sea with G^P_W

Light QCD quarks:		Heavy QCD quarks:	
u	$m_u \sim 5$ MeV	c	$m_c \sim 1500$ MeV
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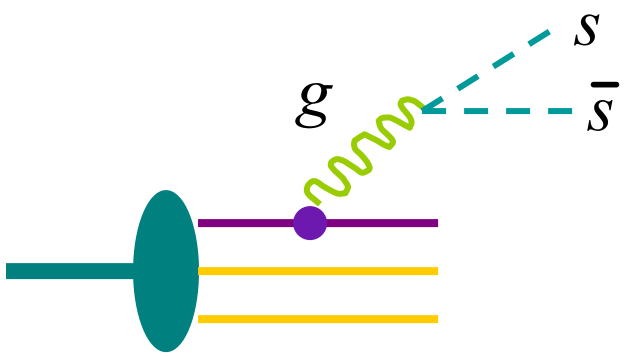
Lives only in the sea



Parity-Violating Electron Scattering

Kaplan and Manohar
McKeown

Neutral Weak Form Factors

$$G^P = Q^u G^u + Q^d G^d + Q^s G^s \Longleftrightarrow \gamma$$

$$G^n = Q^u G^d + Q^d G^u + Q^s G^s \Longleftrightarrow \gamma\text{, isospin}$$

$$G^P{}_W = Q^u{}_W G^u + Q^d{}_W G^d + Q^s{}_W G^s \Longleftrightarrow Z^0$$

SAMPLE (MIT-Bates), HAPPEX (JLab), PVA4 (Mainz), G0 (JLab) $\Rightarrow$ G^u , G^d , G^s

Parity-Violating Electron Scattering

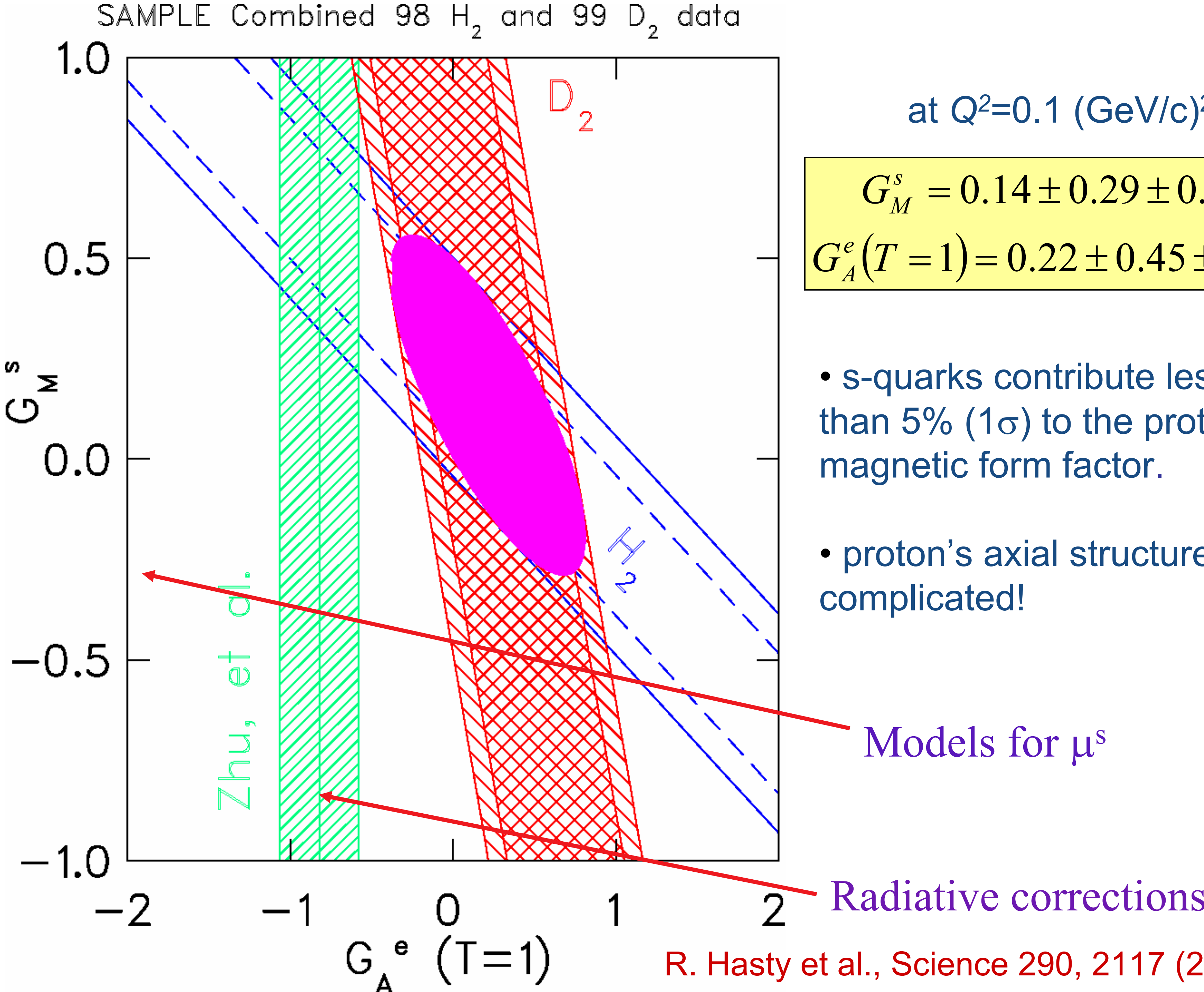
Separating G^E_W , G^M_W , G^A_W

G^M_W , G^A_W SAMPLE

G^M_W , G^E_W HAPPEX, PVA4

G^M_W , G^E_W , G^A_W : Q^2-dependence G0

Published results: SAMPLE, HAPPEX



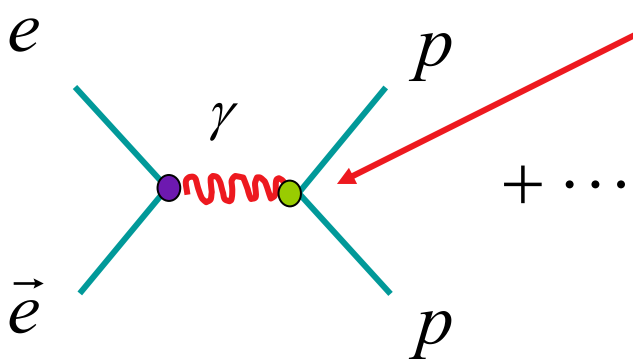
at Q^2=0.1 (GeV/c)^2

$$G_M^s = 0.14 \pm 0.29 \pm 0.31$$
$$G_A^e(T=1) = 0.22 \pm 0.45 \pm 0.39$$

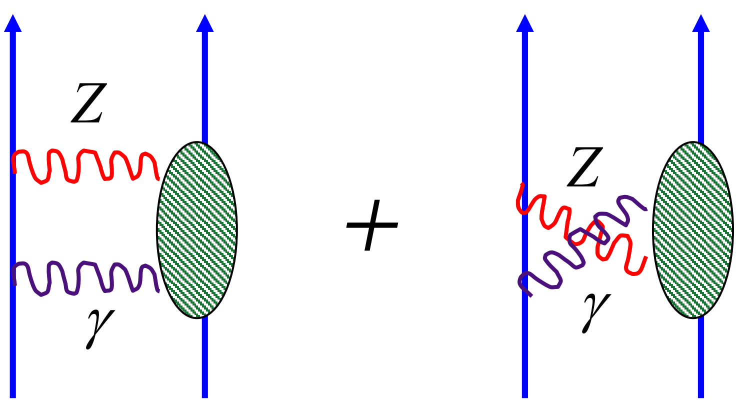
- s-quarks contribute less than 5% (1σ) to the proton's magnetic form factor.
- proton's axial structure is complicated!

R. Hasty et al., Science 290, 2117 (2000).

Axial Radiative Corrections

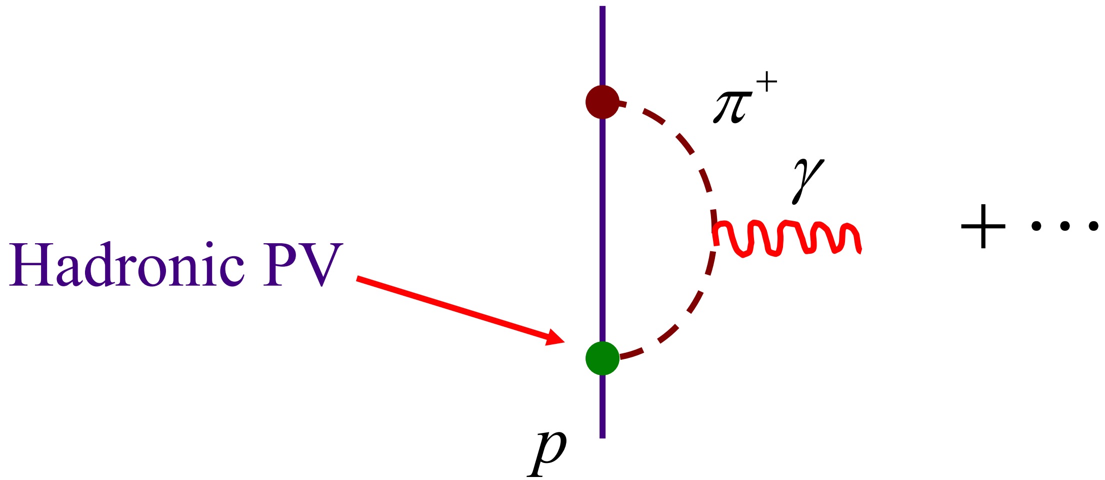


"Anapole" effects : Hadronic Weak Interaction



Nucleon Green's Fn : Analogous effects in neutron β-decay, PC electron scattering…

"Anapole" Effects

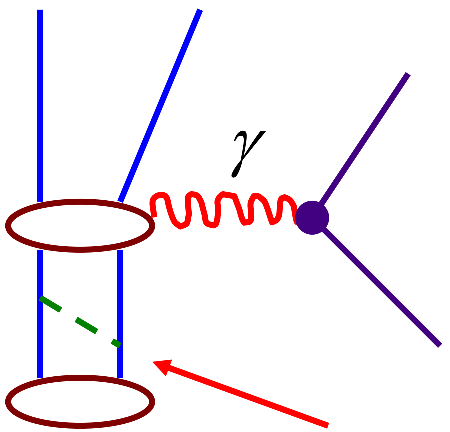


Zhu et al.

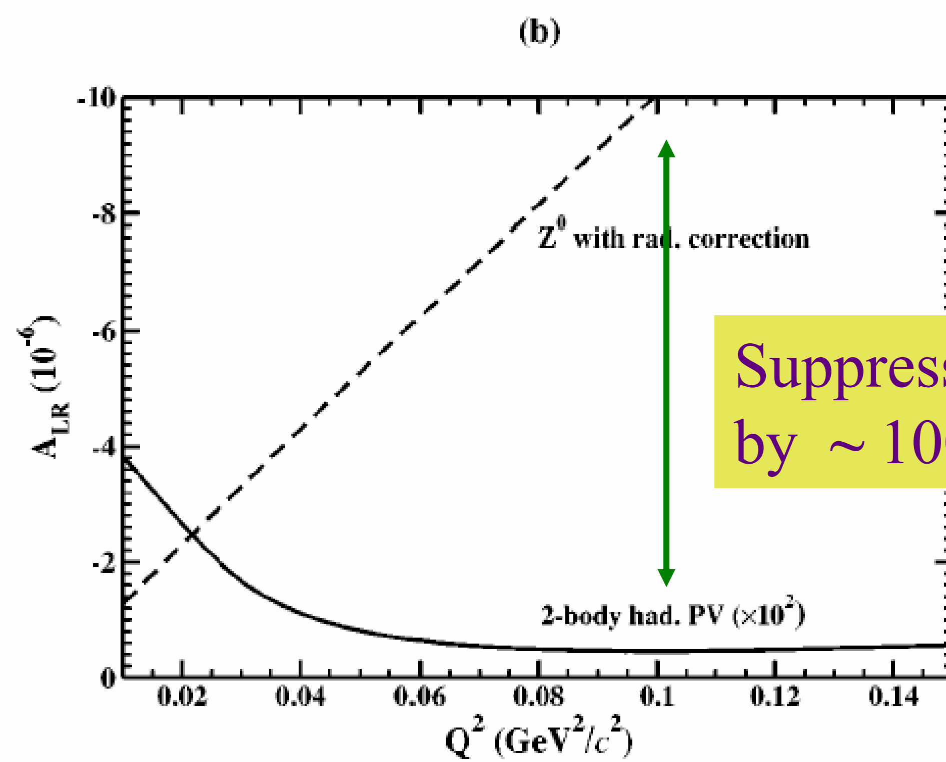
Zhu, Puglia, Holstein, R-M (χPT)
Maekawa & van Kolck (χPT)
Riska (Model)

Can't account for a large reduction in G^e_A

Nuclear PV Effects



PV NN interaction

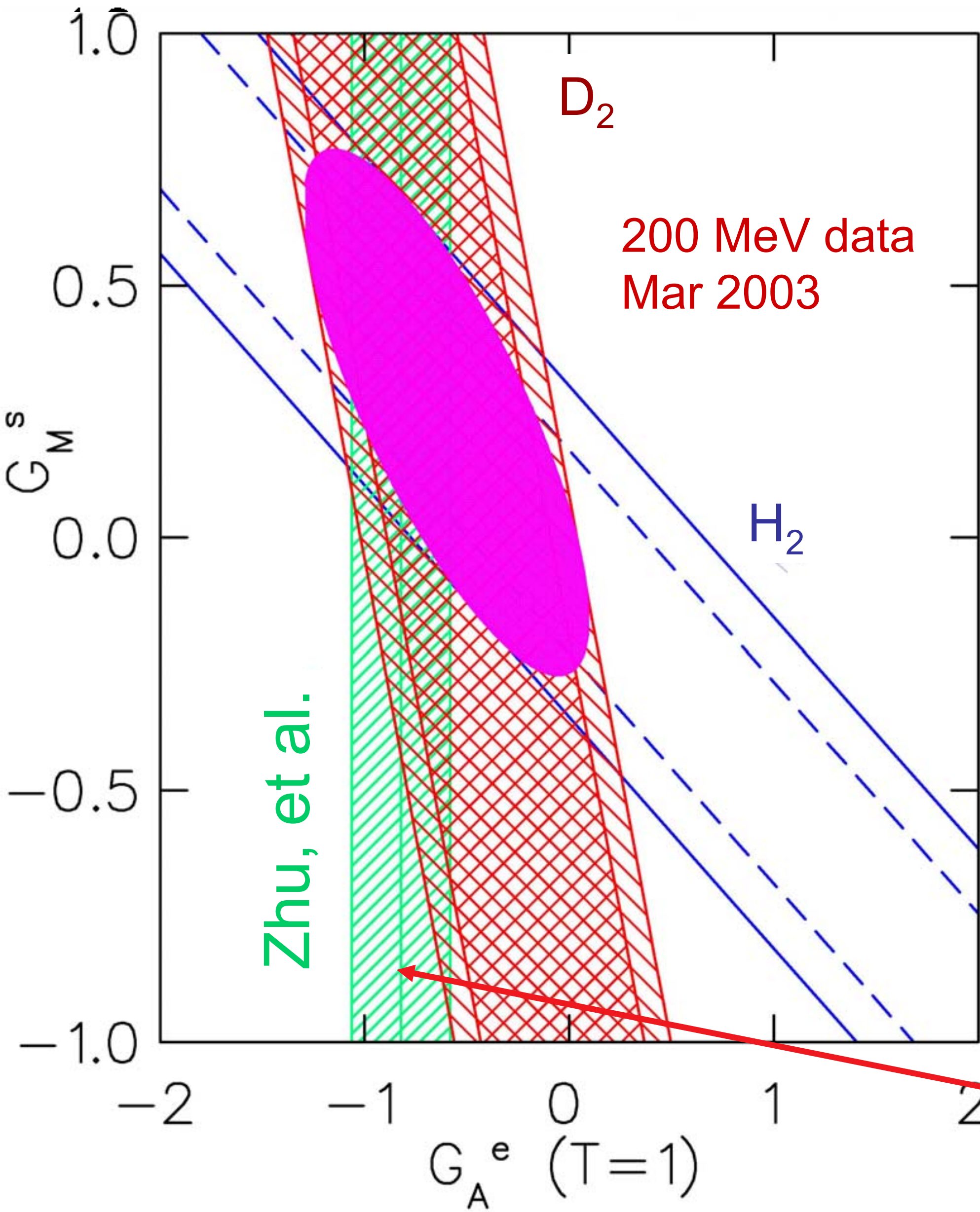


Suppressed by ~ 1000

Carlson, Paris, Schiavilla
Liu, Prezeau, Ramsey-Musolf

SAMPLE Results

R. Hasty et al., Science 290, 2117 (2000).



at Q^2=0.1 (GeV/c)^2

- s-quarks contribute less than 5% (1σ) to the proton's magnetic moment.

200 MeV update 2003:
Improved EM radiative corr.
Improved acceptance model
Correction for π background

125 MeV:
no π background
similar sensitivity
to G_A^e(T=1)

Radiative corrections

E. Beise, U Maryland

Strange Quark Form Factors

Theoretical Challenge:

- Strange quarks don’t appear in Quark Model picture of the nucleon
- Perturbation theory may not apply

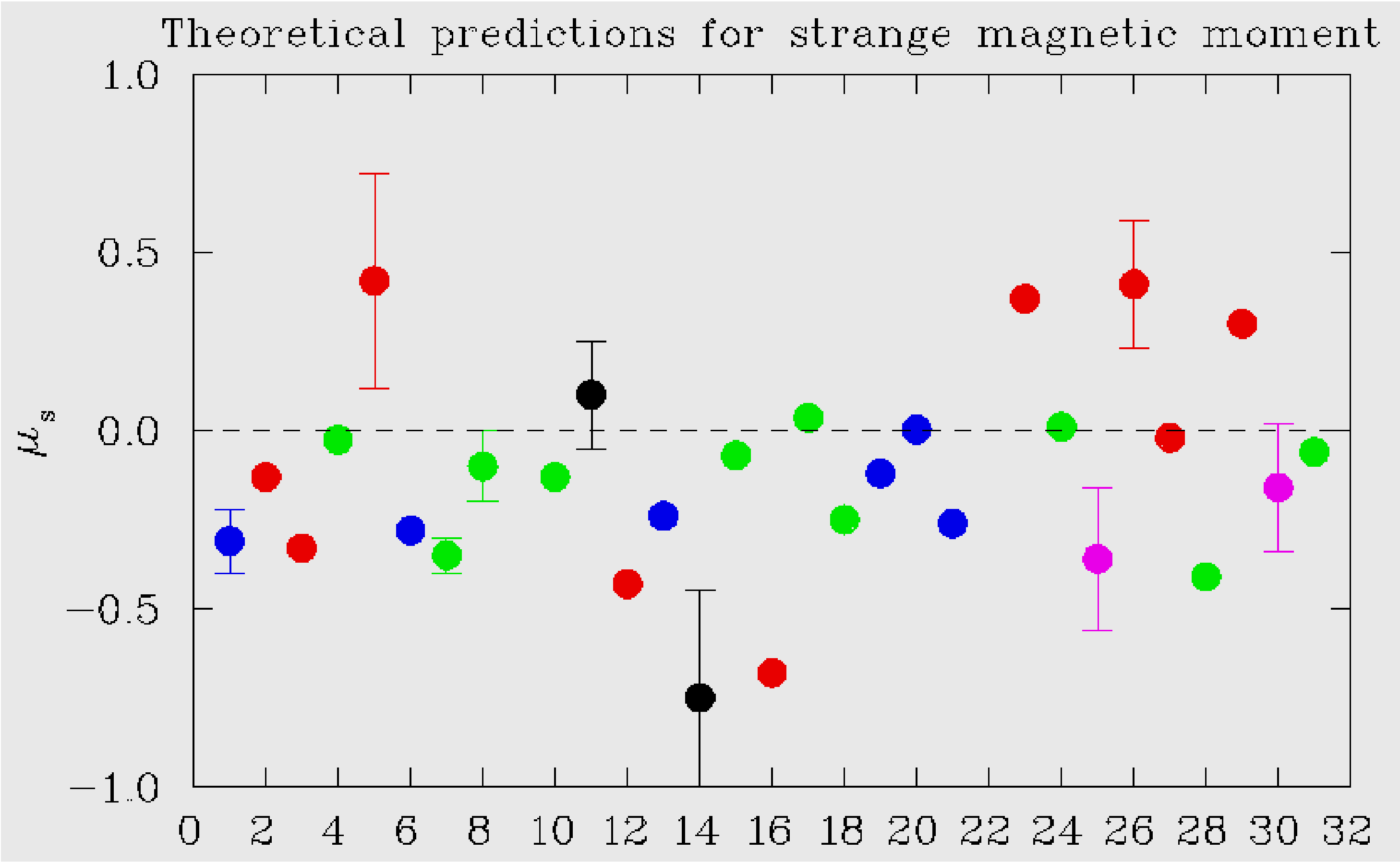
Λ_{QCD} / m_s	$\sim$	1	No HQET
m_K / Λ_χ	$\sim$	1/2	χPT ?

- Symmetry is impotent

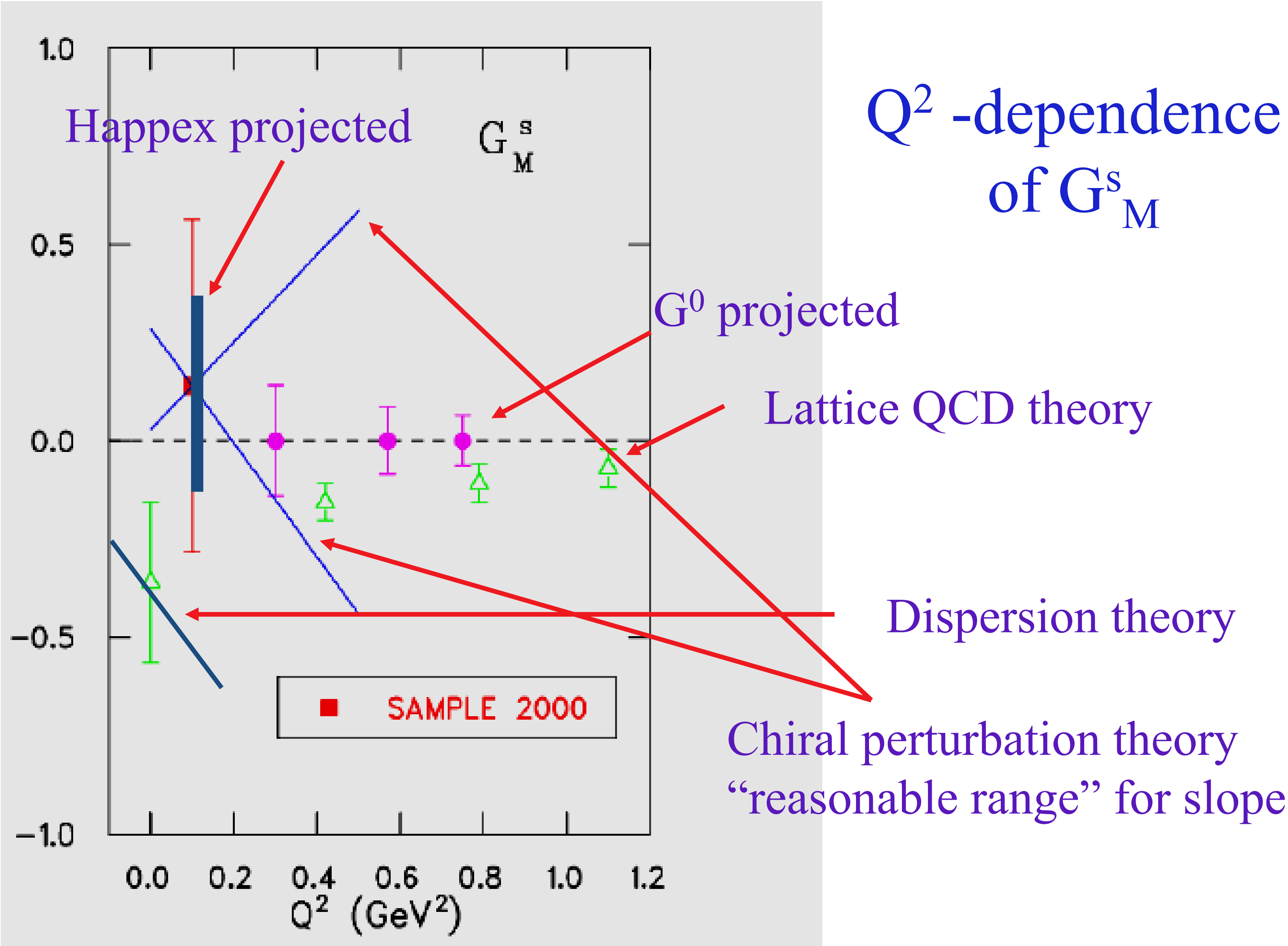
$$J_\mu^{\,s} = J_\mu^{\,B} + 2\, J_\mu^{\,EM,\, I=0}$$

$$\mu_s \equiv G_M^s(Q^2 = 0)$$

Theoretical predictions



Q^2 -dependence of G^s_M



What χPT can (cannot) say

Strange magnetism as an illustration

Ito, R-M
Hemmert, Meissner, Kubis
Hammer, Zhu, Puglia, R-M

$$G_M^s(q^2) = \mu_s + \tfrac{1}{6} q^2 r_{s,M}^2 + \cdots$$

$$\mu_s = \left(2M_N/\Lambda_\chi\right) b_s + \cdots$$

Unknown low-energy constant (incalculable)

Kaon loop contributions (calculable)

What χPT can (cannot) say

Strange magnetism as an illustration

$$G_M^s(q^2) = \mu_s + \frac{1}{6} q^2 r^2_{s,M} + \cdots$$

$$r^2_{s,M} = -\frac{6}{\Lambda_\chi}\left\{\left(\frac{2M_N}{\Lambda_\chi}\right) b_s^r\right.$$

NLO, unknown LEC

$$\left. + \frac{1}{18}(5D^2 - 6DF + 9F^2)\left(\frac{\pi M_N}{m_K} + 7\ln\frac{m_K}{\mu}\right) + \cdots\right\}$$

LO, parameter free

NLO, cancellation

Dispersion theory gives a model-independent prediction

Slope of G_M^s

$$r^2_{s,M} = \frac{6}{\pi} \int_{9m_\pi^2}^{\infty} dt \frac{\mathrm{Im}\, G_M^s(t)}{t^2}$$

Strong interaction scattering amplitudes

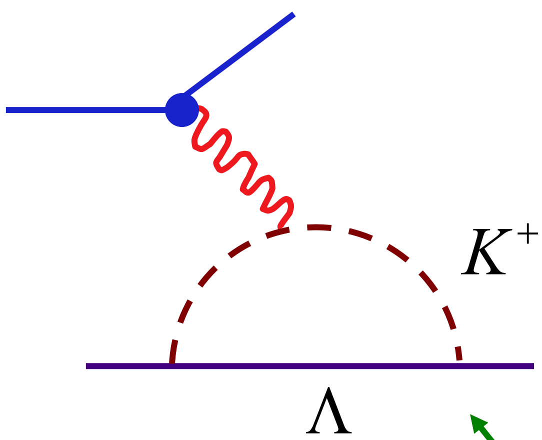
$e^+ e^- \longrightarrow K^+ K^-$, etc.

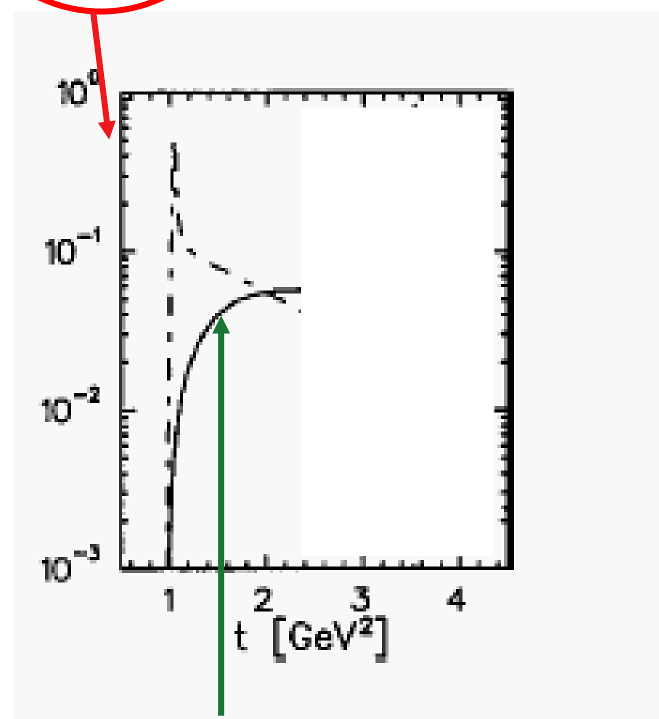
Jaffe
Hammer, Drechsel, R-M

Dispersion theory gives a model-independent prediction

Hammer & R-M

$$r_{s,M}^2 = \frac{6}{\pi} \int_{4m_K^2}^{\infty} dt \, \frac{\mathrm{Im}\, G_M^s(t)}{t^2}$$



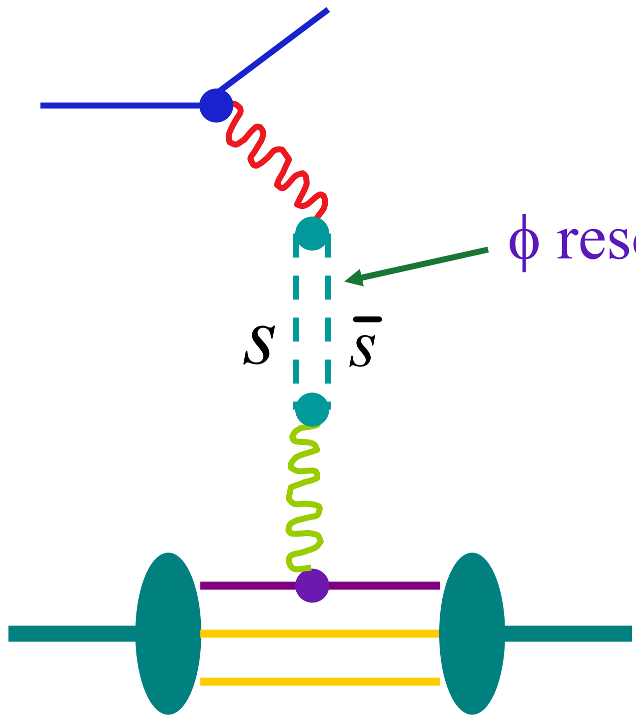


Perturbation theory (1-loop)

Dispersion theory gives a model-independent prediction

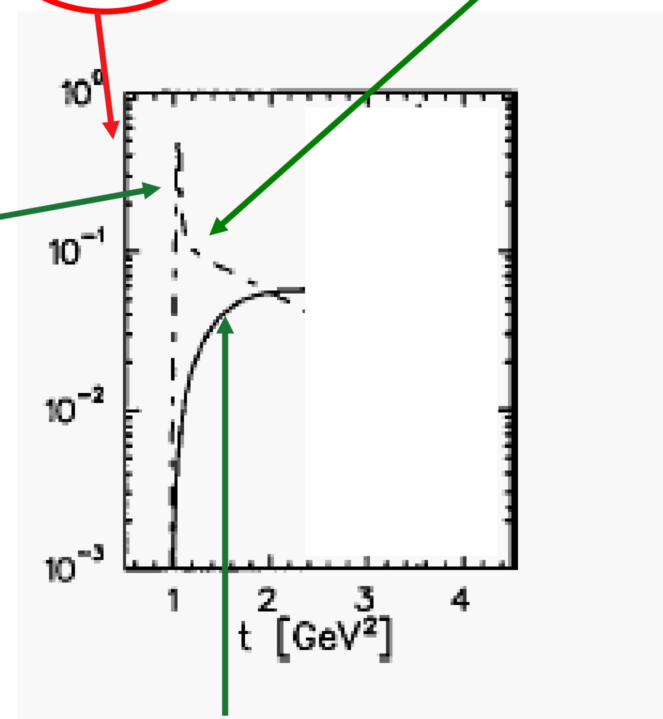
Hammer & R-M

$$r_{s,M}^2 = \frac{6}{\pi}\int_{4m_K^2}^{\infty} dt\,\frac{\mathrm{Im}\,G_M^s(t)}{t^2}$$



ϕ resonance

All orders



Perturbation theory (1-loop)

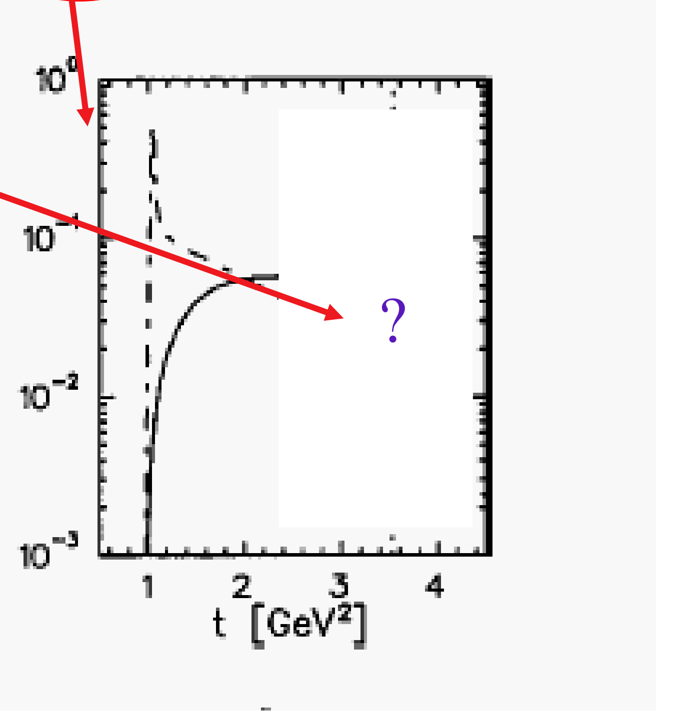
Dispersion theory gives a model-independent prediction

$$r_{s,M}^2 = \frac{6}{\pi}\int_{4m_K^2}^{\infty} dt \frac{\mathrm{Im}G_M^s(t)}{t^2}$$

Can't do the whole integral

- Are there higher mass excitations of s $\bar{s}$ pairs?
- Do they enhance or cancel low-lying excitations?

Experiment will give an answer



PVES and Nucleonic Matter

What is the equation of state of dense nucleonic matter?

We know a lot about the protons, but lack critical information about the neutrons

PVES and Nucleonic Matter

The Z^0 boson probes neutron properties

Donnelly, Dubach, Sick

$$Q_W = Z(1 - 4 \sin^2\theta_W) - N$$

~ 0.1

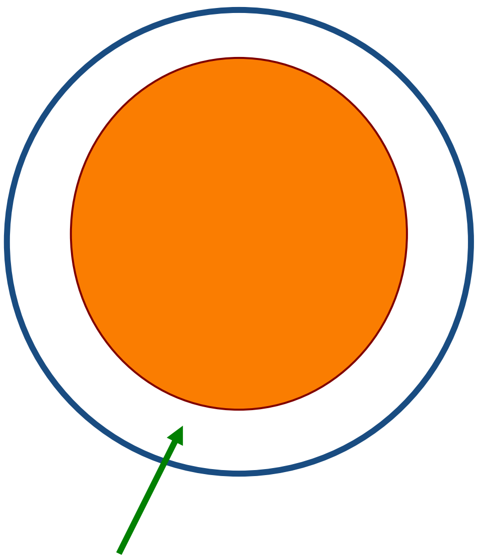
PREX (Hall A): ^{208}Pb

Horowitz, Pollock, Souder, & Michels

PVES and Neutron Stars

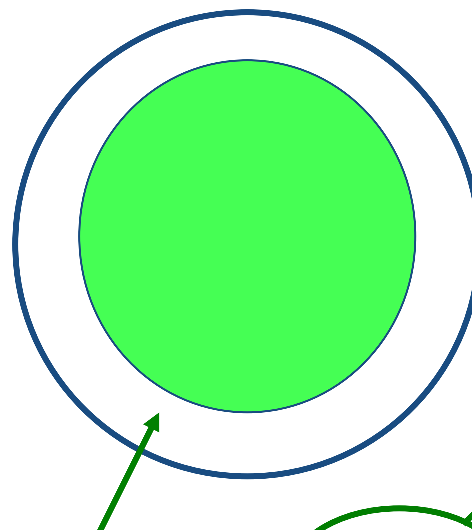
Neutron star

Horowitz & Piekarewicz



Crust thickness decreases with P_n

^{208}Pb

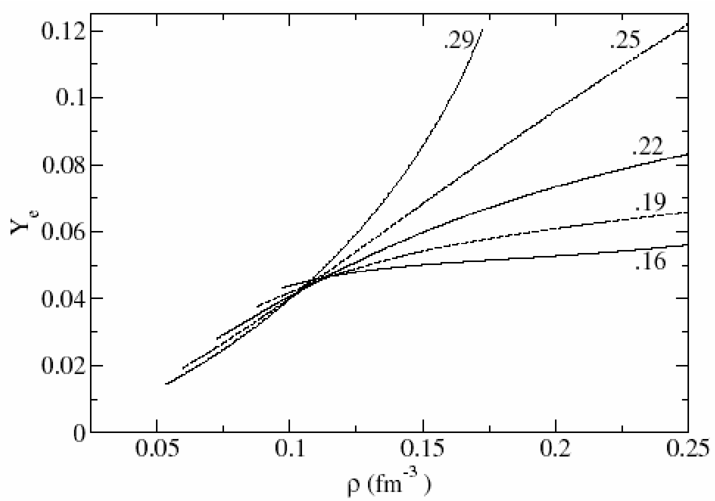


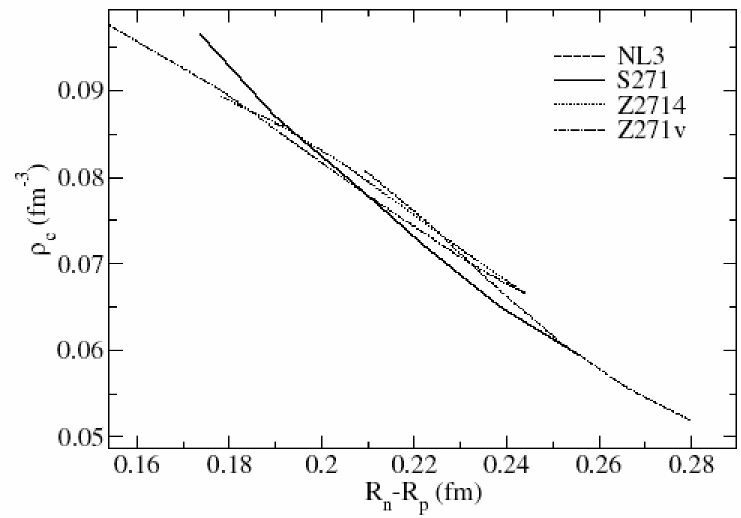
PREX

Skin thickness (R_n-R_p) increases with P_n

PVES and Neutron Stars

Horowitz & Piekarewicz





Neutron star properties are connected to density-dependence of symmetry energy

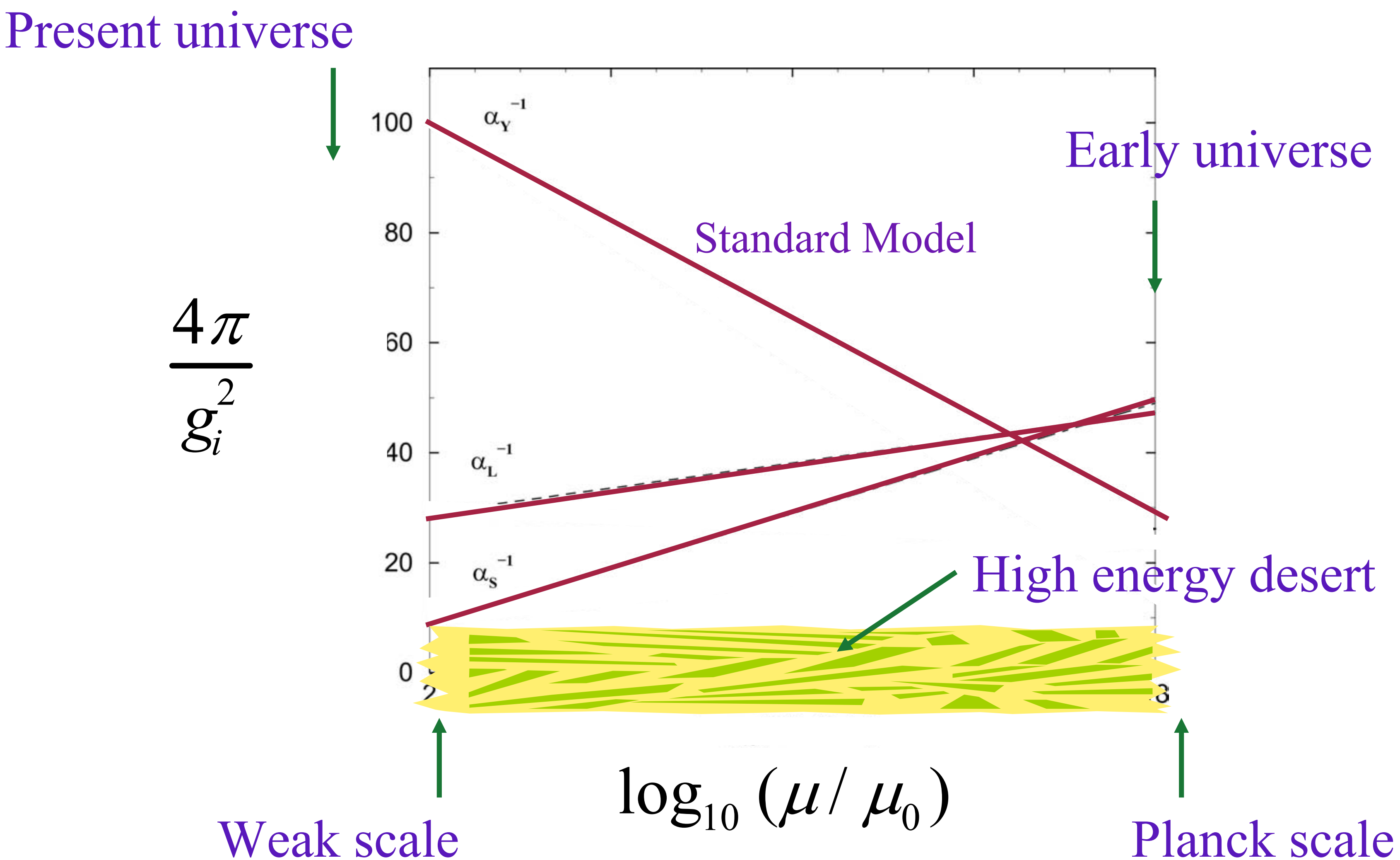
PREX probes R_n-R_p a meter of E (ρ)

PVES and the New Standard Model

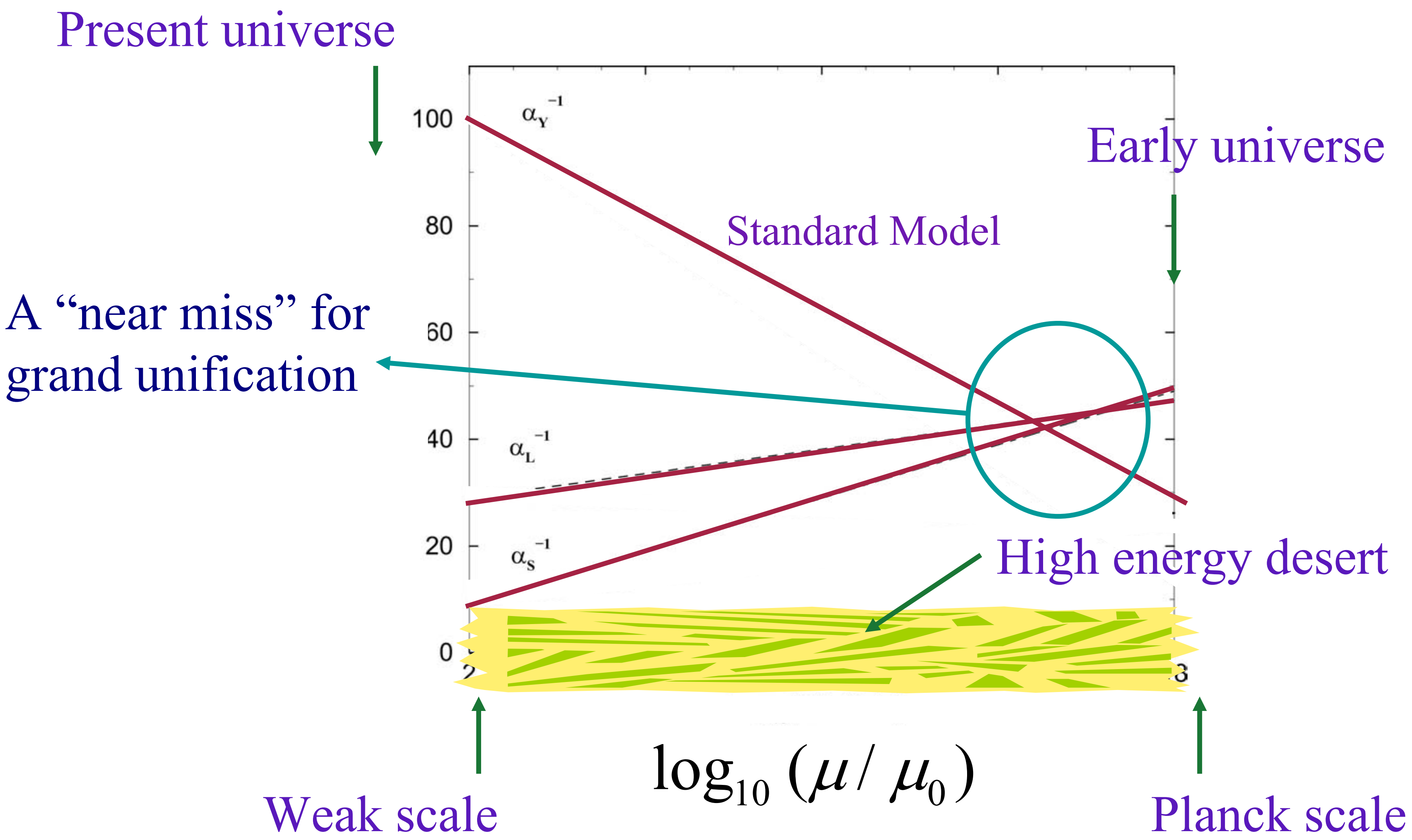
We believe in the Standard Model, but it leaves many unanswered questions

- What were the symmetries of the early Universe and how were they broken?
- What is dark matter?
- Why is there more matter than anti-matter?

PVES and the New Standard Model



PVES and the New Standard Model



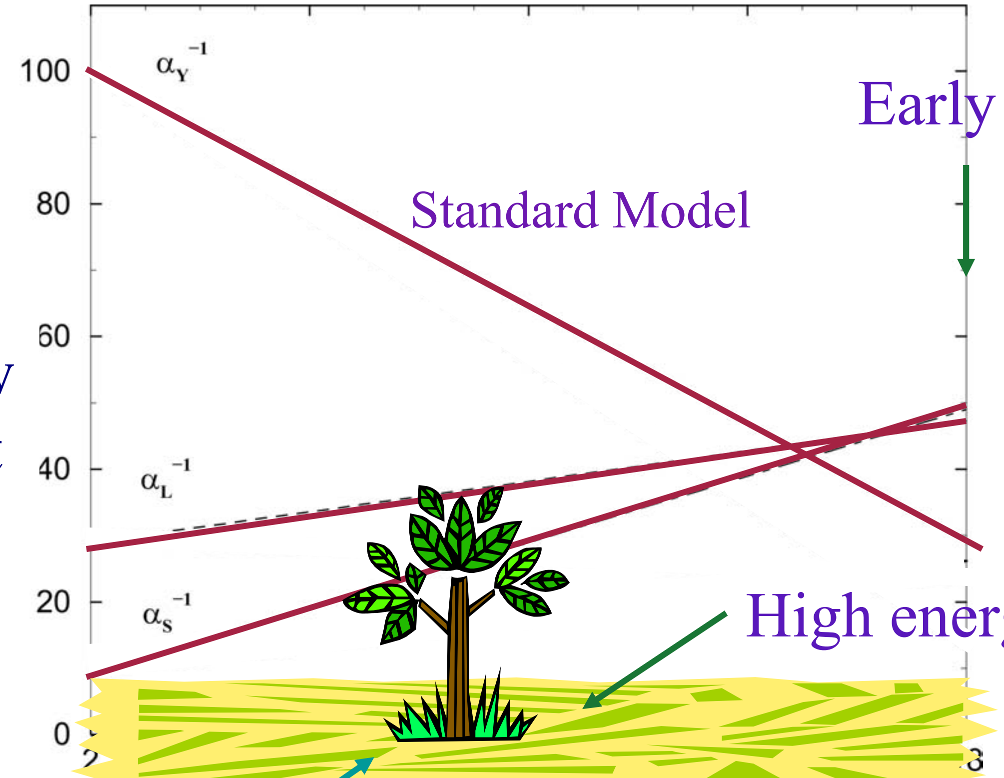
PVES and the New Standard Model

Present universe

Early universe

Weak scale is unstable against new physics in the desert

G_F would be much smaller



High energy desert

$\log_{10}(\mu/\mu_0)$

Weak scale

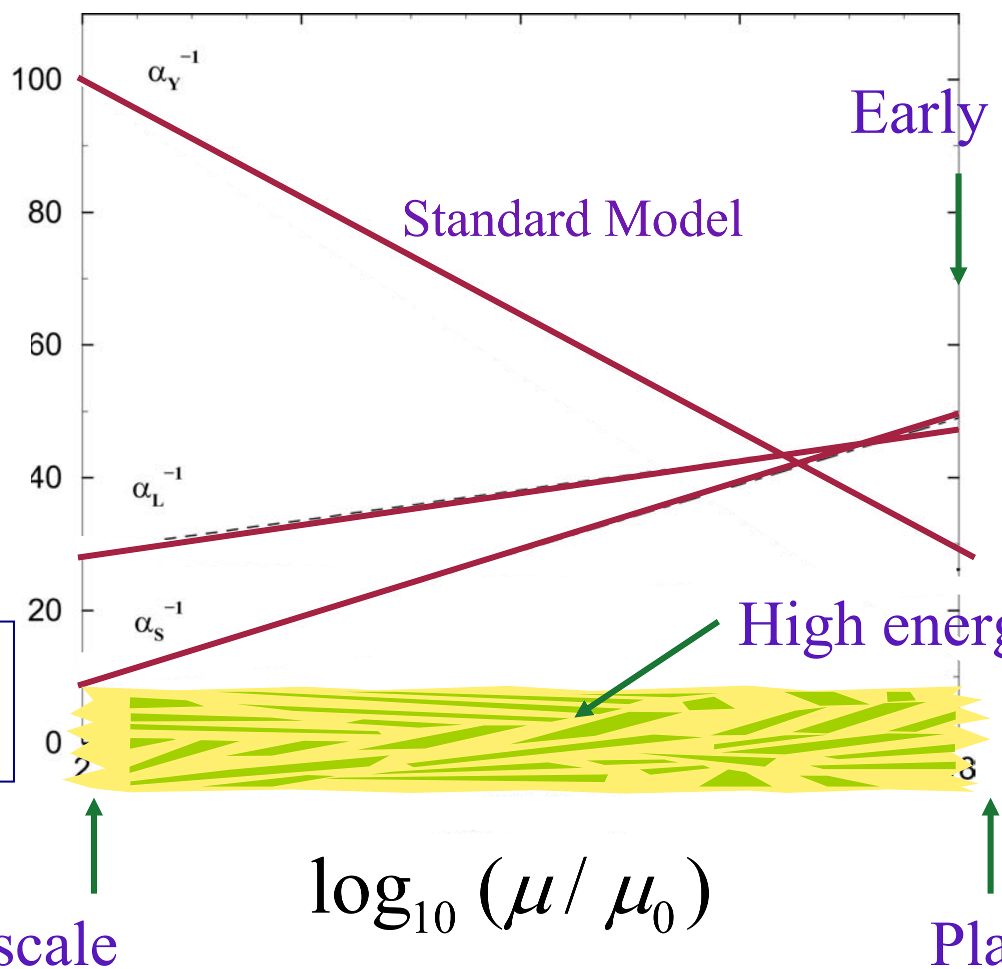
Planck scale

PVES and the New Standard Model

Present universe

Not enough CP-violation for weak scale baryogenesis

$$n_B - n_{\bar{B}} \sim 10^{-10} n_\gamma$$



Neutral current mixing depends on electroweak symmetry

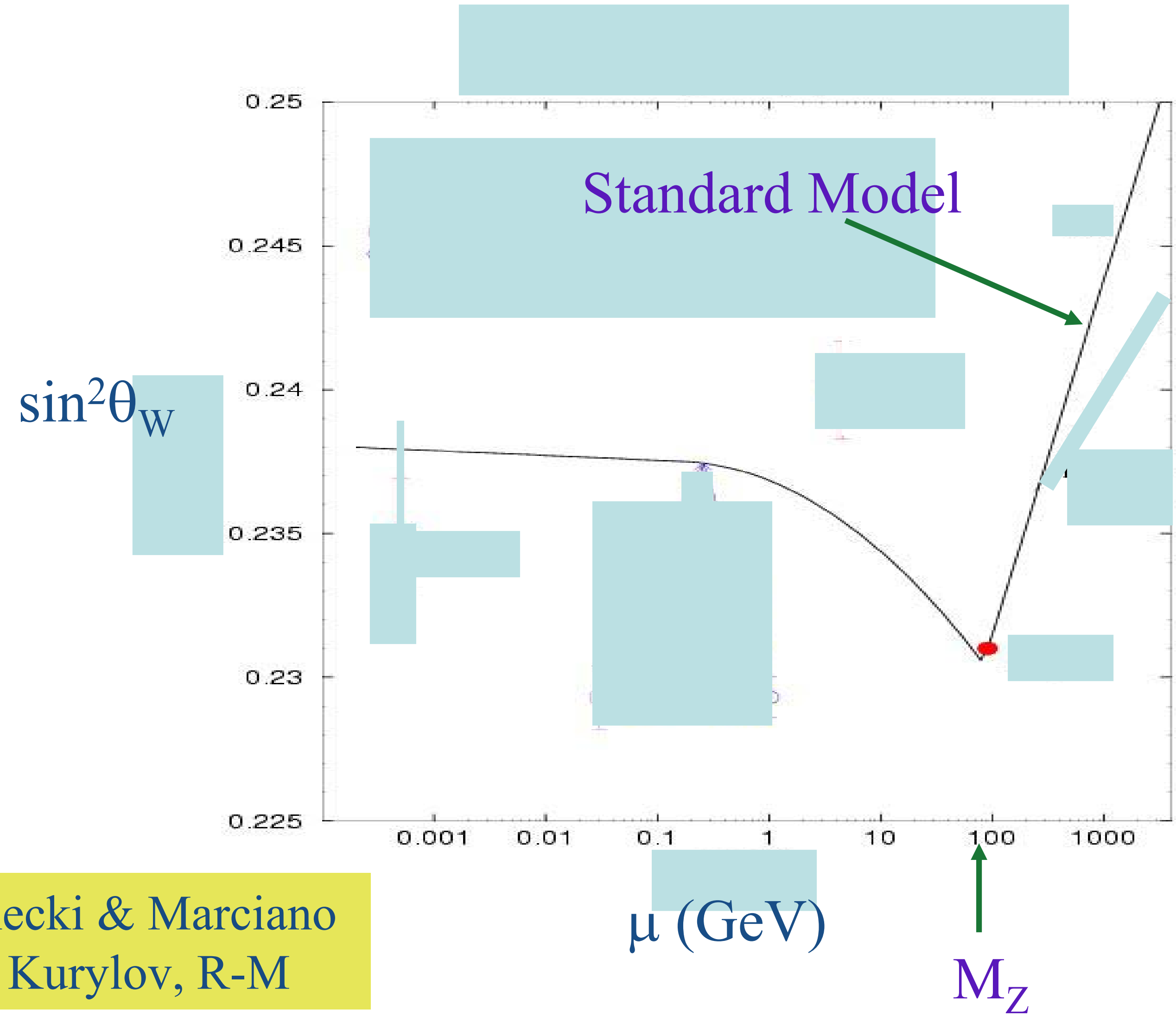
$$J_\mu^{WNC} = J_\mu^0 + 4\,Q \sin^2\theta_W \cdot J_\mu^{EM}$$

$$\sin^2\theta_W = \frac{g_Y^2}{g^2 + g_Y^2}$$

SU(2)$_L$

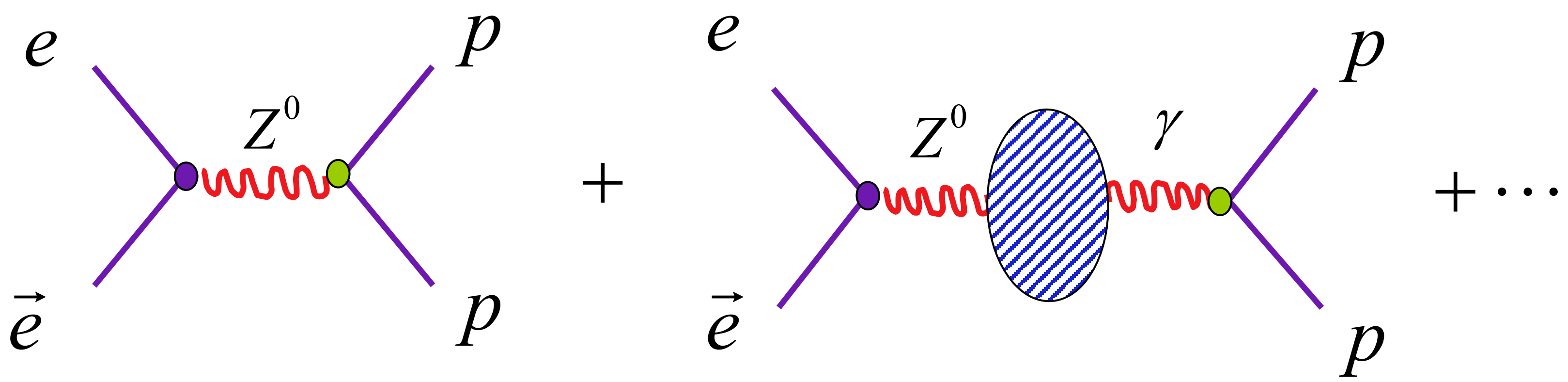
U(1)$_Y$

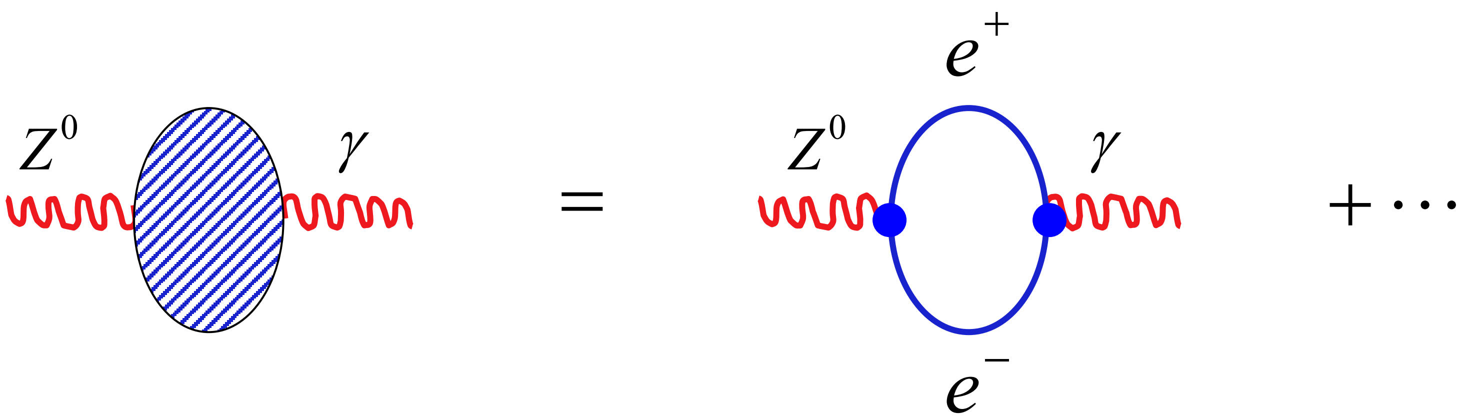
Weak mixing also depends on scale



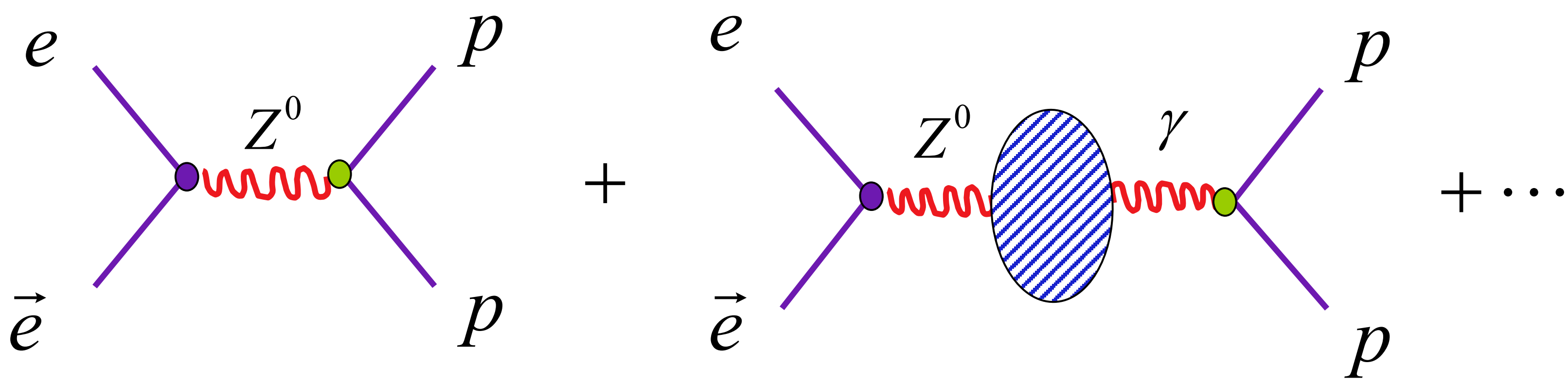
Czarnecki & Marciano
Erler, Kurylov, R-M

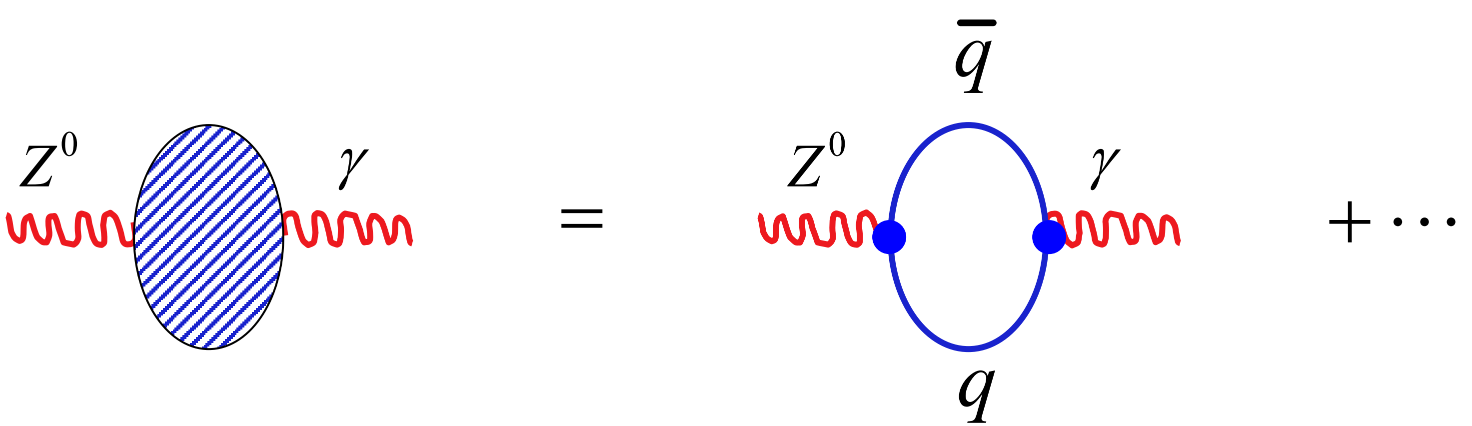
$\sin^2\theta_W(\mu)$ depends on particle spectrum



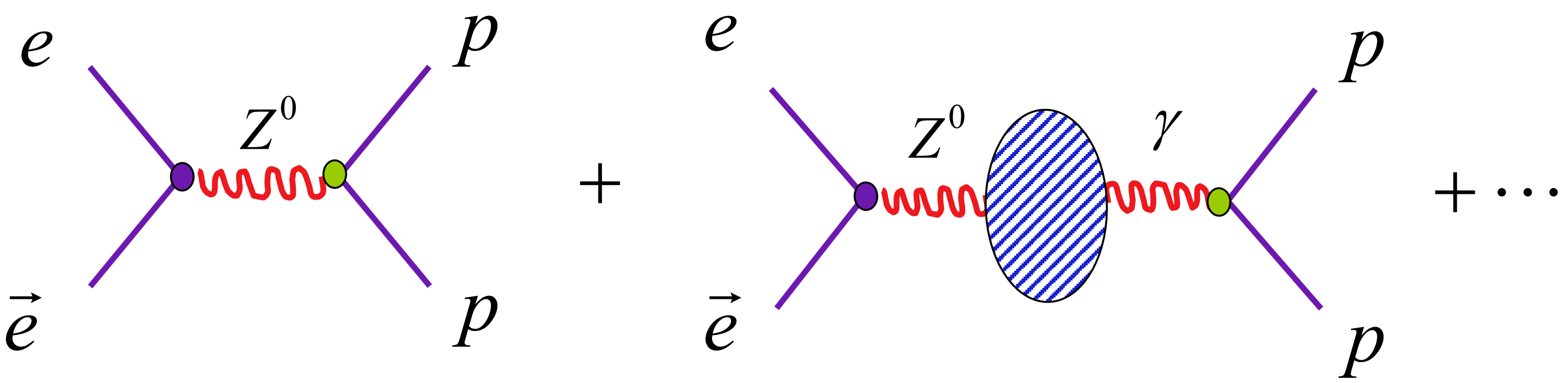


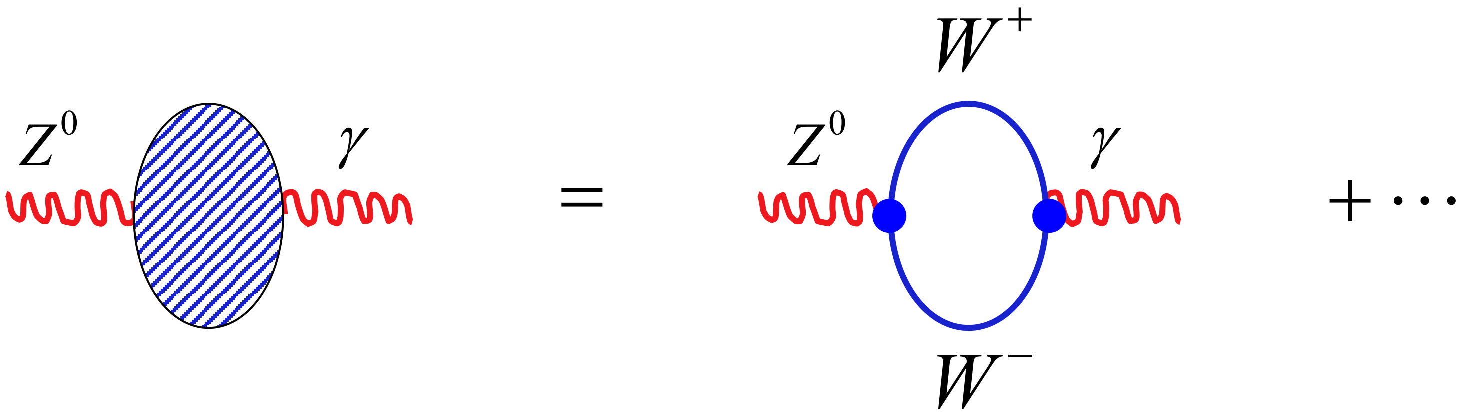
$\sin^2\theta_W(\mu)$ depends on particle spectrum





$\sin^2\theta_W(\mu)$ depends on particle spectrum





New Physics & Parity Violation

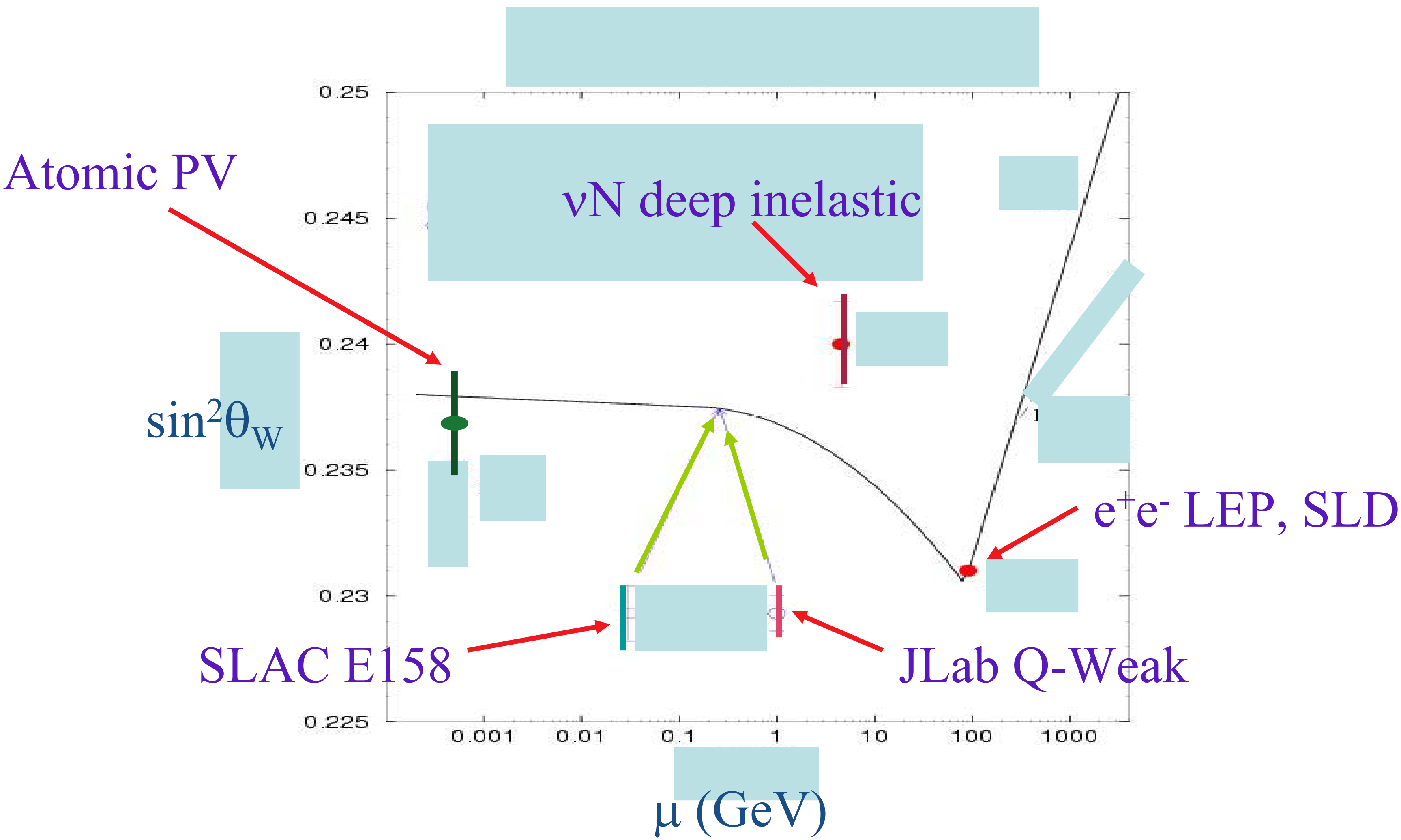
$$Q^{e}_{W} = -1 + 4 \sin^2\theta_W$$

$$Q^{P}_{W} = 1 - 4 \sin^2\theta_W$$

$$Q^{Cs}_{W} = Z(1 - 4 \sin^2\theta_W) - N$$

$\sin^2\theta_W$ is scale-dependent

Weak mixing also depends on scale



Additional symmetries in the early universe can change scale-dependence

Supersymmetry

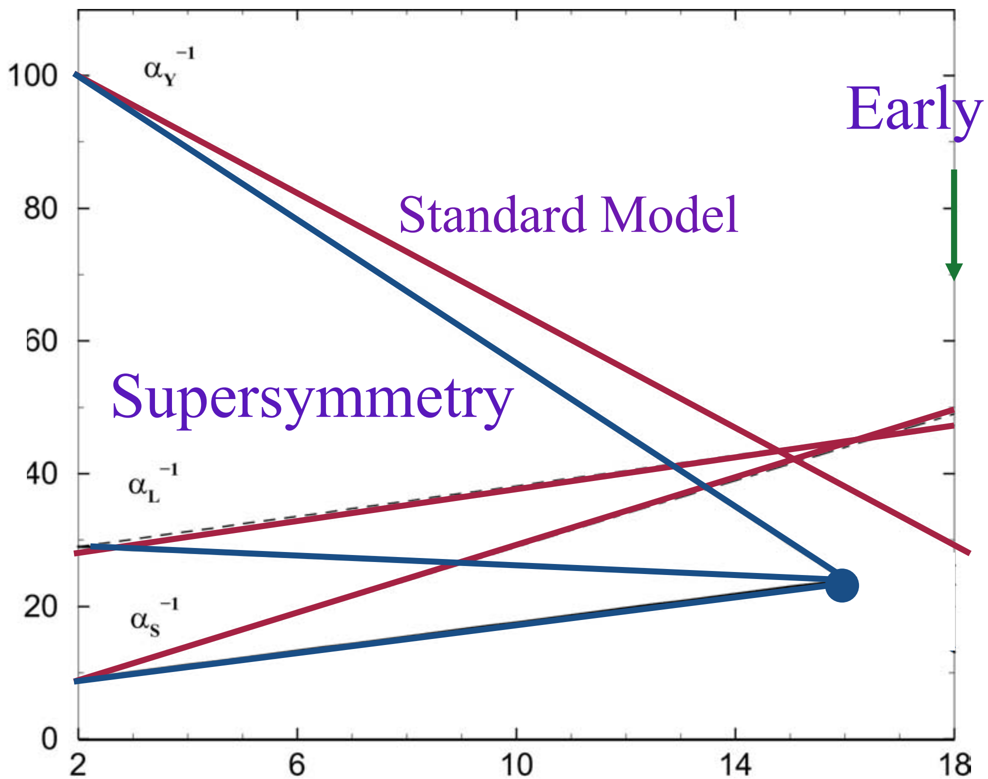
	Fermions		Bosons	
	$e_{L,R}\,,\ q_{L,R}$	$\Longleftrightarrow$	$\tilde{e}_{L,R}\,,\ \tilde{q}_{L,R}$	sfermions
gauginos	$\tilde{W},\tilde{Z},\tilde{\gamma},\tilde{g}$	$\Longleftrightarrow$	W,Z,γ,g	
Higgsinos	$\tilde{H}_u,\tilde{H}_d$	$\Longleftrightarrow$	H	

$$\tilde{W},\tilde{Z},\tilde{\gamma},\tilde{H}_{u,d} \Rightarrow \tilde{\chi}^{\pm},\tilde{\chi}^{0}$$

Charginos,
neutralinos

Electroweak & strong couplings unify with supersymemtry

Present universe



$$\frac{4\pi}{g_i^2}$$

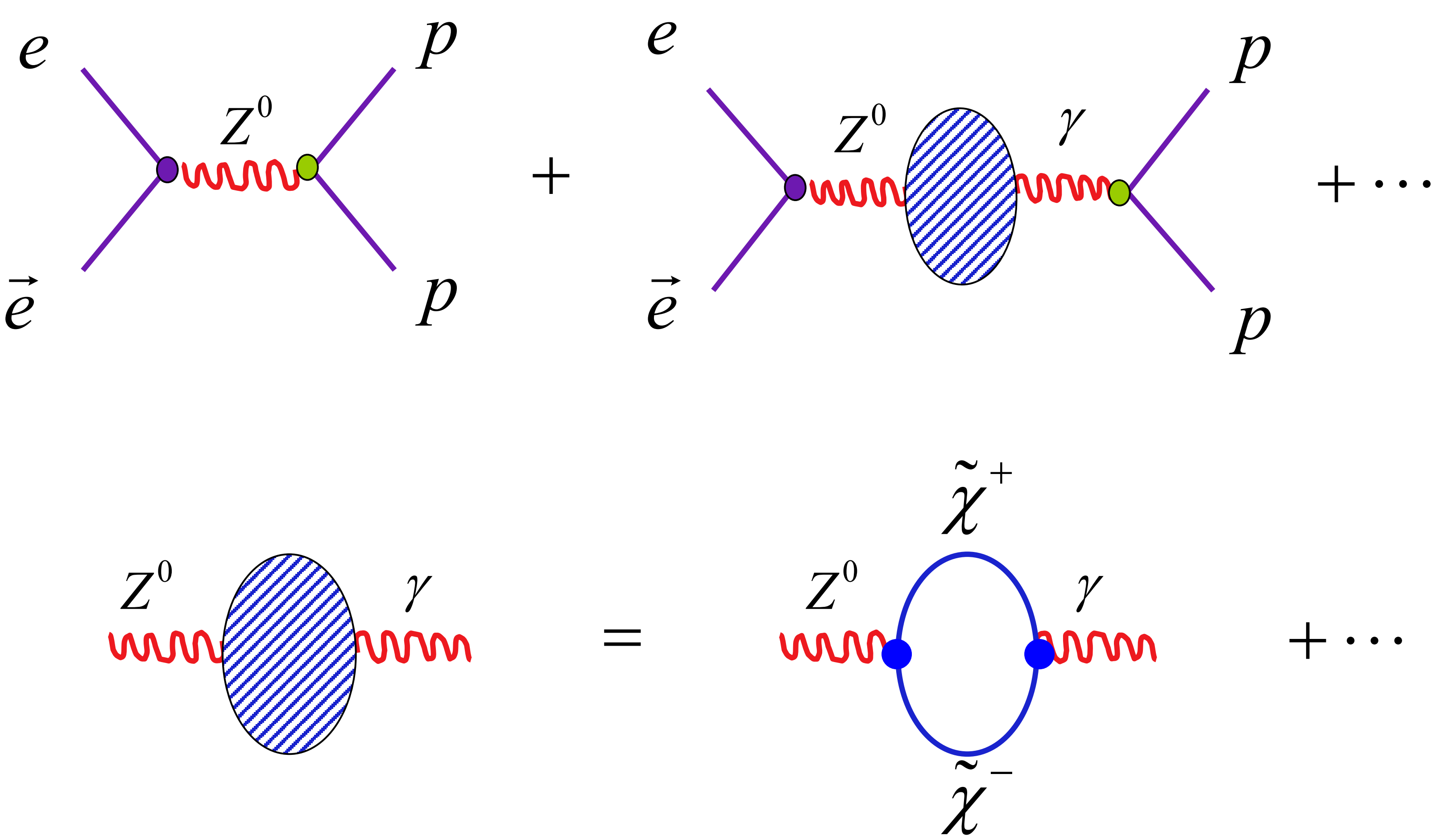
Weak scale &
G_F are protected

$$\log_{10}(\mu/\mu_0)$$

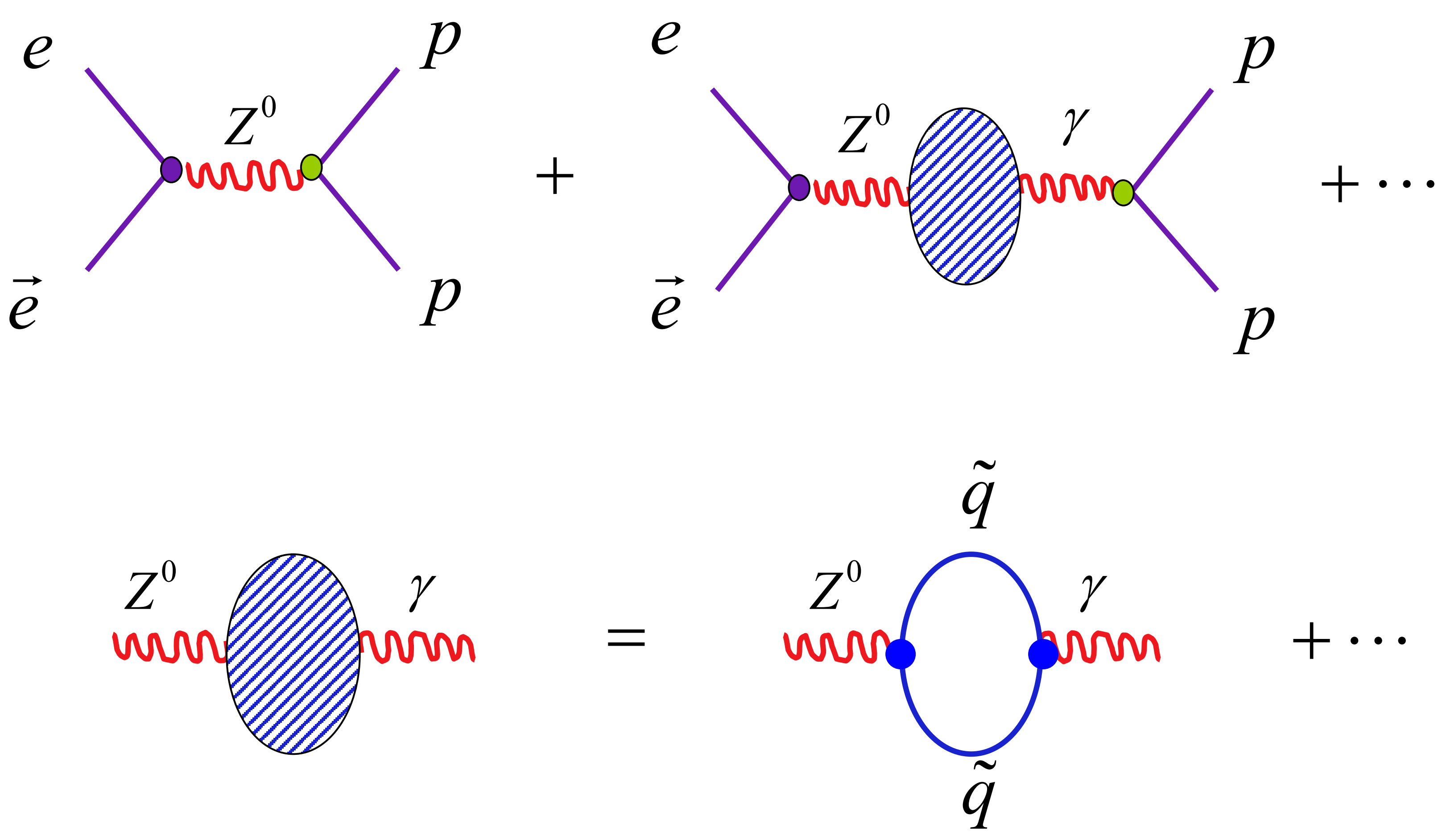
Weak scale

Planck scale

SUSY will change $\sin^2\theta_W(\mu)$ evolution



SUSY will change $\sin^2\theta_W(\mu)$ evolution



Comparing Q_w^e and Q_W^p

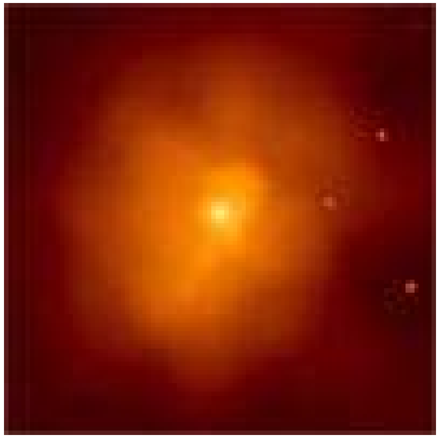
Kurylov, R-M, Su

SUSY loops

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

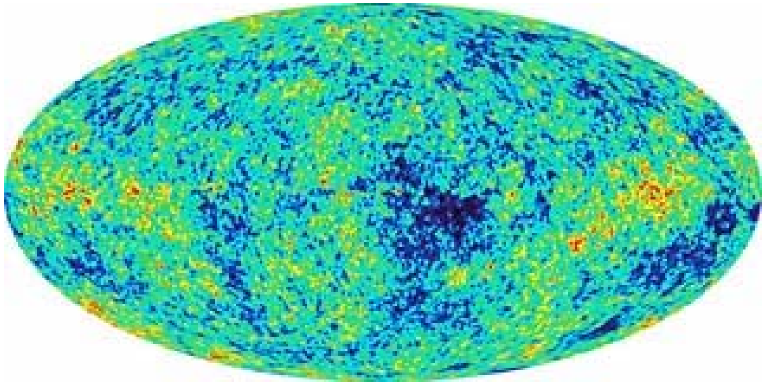
3000 randomly chosen SUSY parameters but effects are correlated

Can SUSY explain dark matter?



Expansion

Rotation curves



Cosmic microwave background

SUSY provides a DM candidate

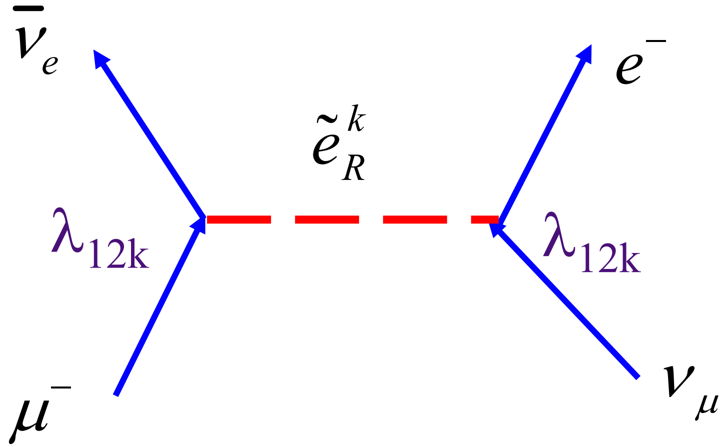
$\tilde{\chi}^0$ Neutralino

- Stable, lightest SUSY particle if baryon (B) and lepton (L) numbers are conserved

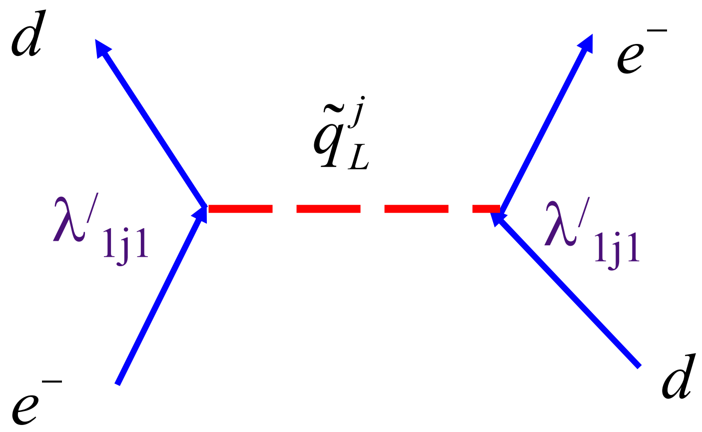
- However, B and L need not be conserved in SUSY, leading to neutralino decay

e.g. $\tilde{\chi}^0 \rightarrow e^+ \mu^- \nu_e$

B and/or L Violation in SUSY can also affect low-energy weak interactions



$\Delta L=1$



$\Delta L=1$

μ-decay, β-decay,…

Q^P_W in PV electron scattering

Comparing Q_w^e and Q_W^p

Kurylov, R-M, Su

SUSY loops

No SUSY
dark matter

$\chi^0 \rightarrow e\mu^+\nu_e$

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

ν is Majorana

RPV 95% CL

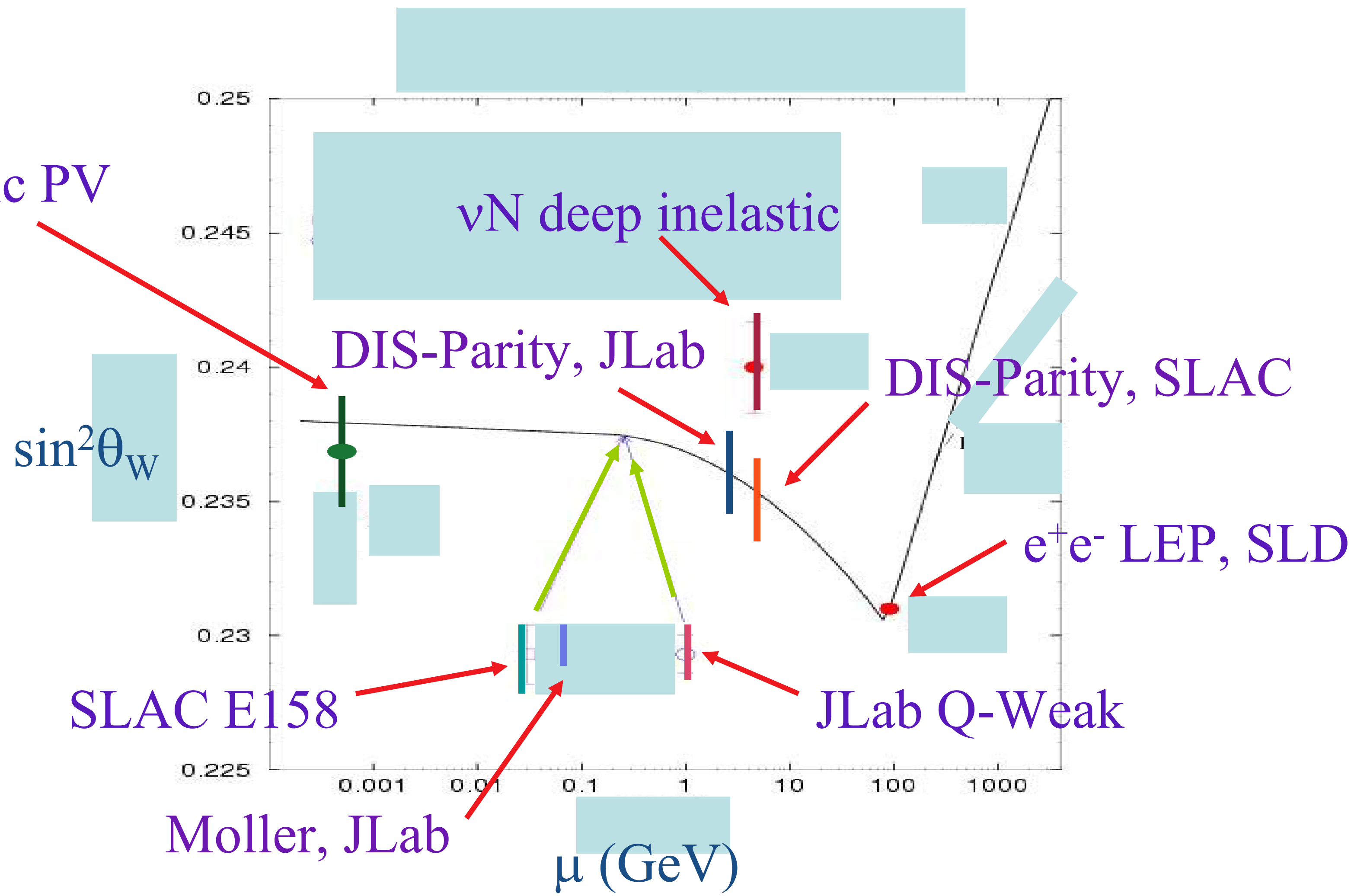
Comparing Q_w^e and Q_W^p

Can be a *diagnostic tool* to determine whether or not

- the early Universe was *supersymmetric*
- there is *supersymmetric* dark matter

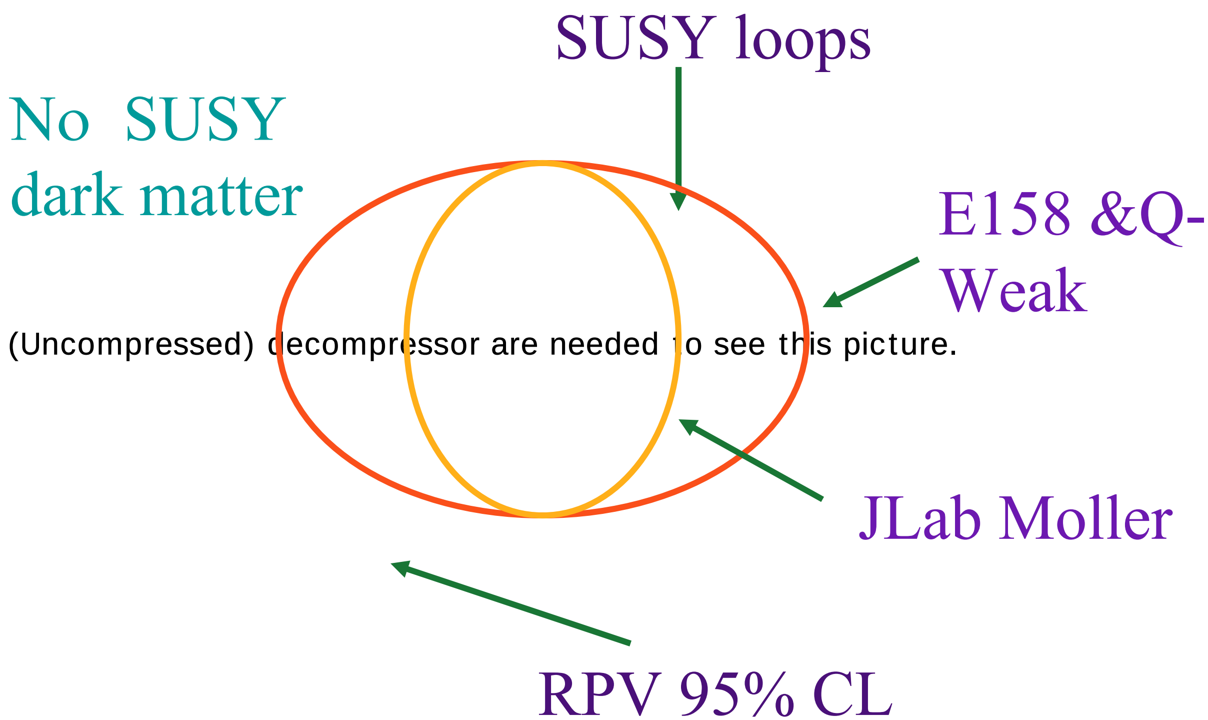
The weak charges can serve a similar diagnostic purpose for other models for high energy symmetries, such as *left-right symmetry, grand unified theories with extra U(1) groups,* etc.

Weak mixing also depends on scale



Comparing Q_w^e and Q_W^p

Kurylov, R-M, Su



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Interpretation of precision measurements

How well do we now the SM predictions? Some QCD issues

Proton Weak Charge

$$A_{LR} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p + F^p(Q^2,\theta)\right]$$

Weak charge

Form factors: MIT, JLab, Mainz

Q^2=0.03 (GeV/c)^2

Q^2>0.1 (GeV/c)^2

Interpretation of precision measurements

How well do we now the SM predictions? Some QCD issues

Proton Weak Charge

$$A_{LR} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p + F^p(Q^2,\theta)\right]$$

$F^P(Q^2, \theta \to 0) \sim Q^2$

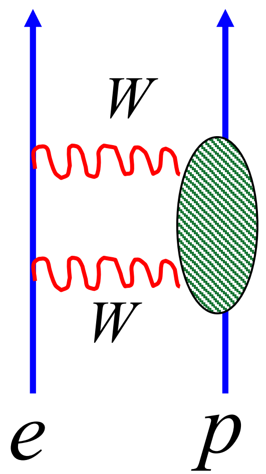
Use χPT to extrapolate in small Q^2 domain and current PV experiments to determine LEC's

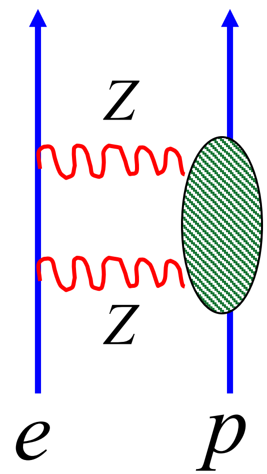
Summary

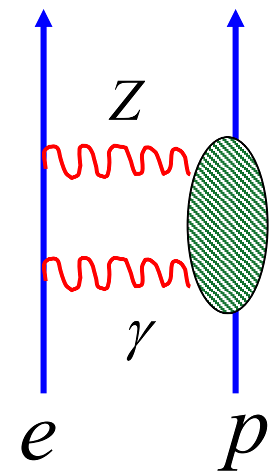
- Parity-violating electron scattering provides us with a well-understood tool for studying several questions at the forefront of nuclear physics, particle physics, and astrophysics:
  - Are sea quarks relevant at low-energies?
  - How compressible is neutron-rich matter
  - What are the symmetries of the early Universe?
- Jefferson Lab is *the* parity violation facility
- We have much to look forward to in the coming years

QCD Effects in Q_W^P

Box graphs







$\delta Q_W \sim 26\%$

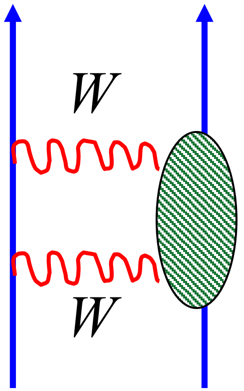
$\delta Q_W \sim 3\%$

$\delta Q_W \sim 6\%$

$k_{loop} \sim M_W$: pQCD

$\Lambda_{QCD} < k_{loop} < M_W$:
non-perturbative

Box graphs, cont'd.



Protected by symmetry

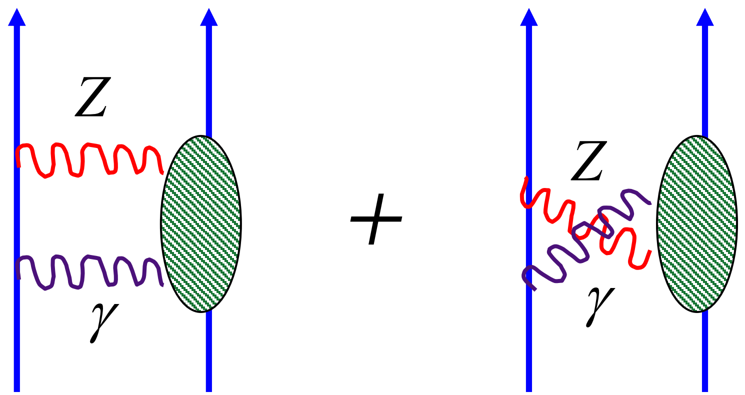
$$M_{WW} = -\frac{G_F}{2\sqrt{2}}\frac{\hat{\alpha}}{4\pi\hat{s}^2}\left[2+5\left(1-\frac{\alpha_s(M_W^2)}{\pi}\right)\right]$$

Short-distance correction: OPE

$\delta Q_W^p(\mathrm{QCD}) \sim -0.7\%$ WW

$\delta Q_W^p(\mathrm{QCD}) \sim -0.08\%$ ZZ

Box graphs, cont'd.

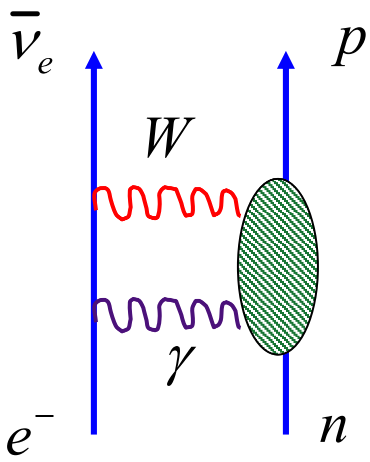


Long-distance physics: not calculable

$$M_{Z\gamma} = -\frac{G_F}{2\sqrt{2}}\frac{5\hat{\alpha}}{2\pi}\left(1-4\hat{s}^2\right)\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right)+C_{\gamma Z}(\Lambda)\right]$$

Fortuitous suppression factor: box + crossed ~ $\varepsilon^{\mu\nu\alpha\beta}\, k_\nu\, J_\alpha^{\gamma}\, J_\beta^{Z} \sim A^\mu$ $\Longrightarrow$ $g_v^{e} = (-1+4\sin^2\theta_W)$

Neutron β-decay



$$M_{W\gamma} = \frac{G_F}{\sqrt{2}} \frac{\hat{\alpha}}{2\pi} \left[\ln\left(\frac{M_Z^2}{\Lambda^2} \right) + C_{\gamma W}(\Lambda) \right]$$

$|\delta C_{\gamma W}| < 2$ to avoid exacerbating CKM non-unitarity

$|\delta C_{\gamma Z}| < 2 \Longrightarrow \delta Q_W^p < 1.5\%$